Dickinson
Research Extension Center
2021 Annual Report

Range-Forage-Livestock-Agronomy-Soils
Outreach




NDSU Research and Extension Staff Involved with the
Dickinson Research Extension Center

Current Staff - 2021

Chris Augustin	Director/Soil Scientist
Ryan Buetow	Cropping Systems Specialist
Doug Landblom	Associate Research Extension Center Specialist
Llewellyn Manske	Scientist of Rangeland Research
Glenn Martin	Research Specialist
Dean Nelson	Ag Research Technician
Phyllis Oakland	Administrative Assistant
Garry Ottmar	Livestock Research Specialist
Wanda Ottmar	Research Technician
Robert Paluck	Ag Research Technician
Sheri Schneider	Information Processing Specialist
Michael Strode	Computer Technician
Lee Tisor	Research Specialist
Timothy Winch	Ag Research Specialist

2021 Seasonal/Temporary Employees
John Urban-Michele Stoltz-Eve Sticka-Jon Sticka-Chuck WannerTom Grey
Samuel Olorunkoya-Mariah McLaughlin-Elizabeth Bardot-Iris Dukart-Austin Haider

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RESEARCH EXTENSION CENTER

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2021 Variety Trials

Grassland Research

Agronomy Research

Livestock Research

2021 Hard Red Spring Wheat - Recrop **Dickinson, ND**

							--------- Grain Yield---------			Average Yield	
Variety	Days to Head	Seeds per Pound	KWT	Plant Height	Test Weight	Protein	2019	2020	2021	2 Year	3 Year
			g/1000	in	lbs/bu	%	----------bu/ac----------			----bu/ac----	
AAC Concord	67	15,977	28.4	18	58.7	18.0	--	43.5	19.8	31.6	--
AP Gunsmoke CL2	65	16,849	27.0	18	58.5	18.3	--	45.8	22.7	34.3	--
AP Murdock	65	18,307	24.9	16	57.5	18.3	--	42.0	15.9	28.9	--
AP Smith	68	16,465	27.6	16	59.7	17.9	--	43.8	19.5	31.6	--
Bolles	67	15,626	29.1	20	59.9	20.3	38.4	38.6	14.3	26.5	30.4
CAG-Justify	67	15,840	28.7	19	56.8	19.7	--	--	16.1	--	--
CAG-Reckless	66	15,955	28.5	19	60.3	18.8	--	--	19.0	--	--
CP 3099A	69	12,645	35.9	16	59.3	18.5	--	--	12.6	--	--
CP 3119A	70	12,991	35.0	15	56.1	17.4	--	--	17.4	--	--
CP 3188	66	15,838	28.7	18	59.4	17.0	--	--	24.4	--	--
CP 3530	68	16,188	28.1	20	58.4	18.8	52.0	44.4	19.8	32.1	38.7
CP 3915	65	16,416	27.8	18	60.3	17.9	51.5	44.5	21.7	33.1	39.2
Dagmar	64	14,866	30.5	17	59.0	18.1	--	44.8	22.3	33.6	--
Driver	67	15,892	28.6	20	61.4	17.9	--	45.4	21.0	33.2	--
Dyna-Gro Ambush	65	16,112	28.2	18	60.0	17.6	46.5	40.8	17.6	29.2	34.9
Dyna-Gro Ballistic	66	16,050	28.4	18	58.8	18.1	--	48.5	17.6	33.0	--
Dyna-gro Commander	66	16,195	28.0	17	59.0	17.8	47.2	40.7	18.8	29.7	35.6
Elgin-ND	65	17,639	25.7	18	59.0	18.0	47.3	43.8	18.4	31.1	36.5
Faller	67	15,488	29.3	19	58.7	17.9	51.2	46.8	18.1	32.4	38.7
Glenn	65	17,062	26.6	19	60.8	17.5	44.8	37.3	19.6	28.4	33.9
LCS Buster	69	15,285	29.7	18	59.6	18.7	--	52.2	12.2	32.2	--
LCS Cannon	63	17,629	25.8	20	60.0	16.7	47.3	44.4	21.0	32.7	37.5
LCS Rebel	64	14,973	30.3	19	59.7	18.4	48.9	44.4	23.2	33.8	38.8
LCS Trigger	69	16,470	27.6	17	59.9	18.4	47.1	51.6	14.7	33.2	37.8
Lang-MN	67	19,178	23.7	18	58.2	18.7	51.2	42.6	18.3	30.5	37.4
Lanning	65	16,551	27.4	18	56.7	18.2	49.2	44.4	19.4	31.9	37.6
MN Washburn	67	16,866	26.9	17	58.8	18.0	48.6	40.1	19.5	29.8	36.1
MN Torgy	66	16,461	27.6	17	60.2	19.1	--	45.4	17.3	31.3	--
MS Barracuda	63	14,632	31.0	18	58.4	18.3	36.8	36.4	23.0	29.7	32.1
MS Cobra	66	16,300	27.9	18	60.2	18.6	--	--	20.3	--	--
MS Ranchero	63	16,490	27.5	18	57.4	17.4	--	47.5	19.3	33.4	--
ND Frohberg	67	15,385	29.5	20	59.5	18.6	48.2	41.2	16.8	29.0	35.4
ND-VitPro	65	16,124	28.1	18	60.5	18.0	44.7	38.9	19.2	29.0	34.2
PFS Buns	70	16,216	28.0	15	54.8	21.1	--	--	5.0	--	--
SY 611 CL2	65	17,530	25.9	16	58.8	17.7	49.8	44.2	20.8	32.5	38.3
Sy Ingmar	68	17,569	25.9	16	59.4	18.8	46.8	43.3	16.2	29.7	35.4
SY Longmire	67	15,729	28.8	17	59.6	18.8	49.8	43.0	15.0	29.0	35.9
SY McCLoud	67	15,170	29.9	17	60.0	18.4	46.2	39.9	16.9	28.4	34.3
SY Rockford	68	15,583	29.1	16	57.6	18.9	54.0	47.5	12.5	30.0	38.0
Sy Soren	66	18,056	25.2	17	58.2	19.0	48.6	40.5	12.6	26.5	33.9
Sy Valda	67	16,513	27.5	16	59.3	18.8	47.0	46.6	15.5	31.0	36.3
TCG-Heartland	65	15,719	29.0	16	59.6	18.5	43.9	41.0	15.6	28.3	33.5
TCG-Spitfire	69	14,083	32.3	15	59.7	18.5	52.6	47.7	13.0	30.3	37.8
TCG-Wildcat	68	15,551	29.2	16	59.9	18.3	--	47.3	19.0	33.2	--
WB 9479	66	16,317	27.9	15	59.4	19.1	--	--	13.4	--	--

WB 9590	64	15,670	29.0	15	59.2	18.6	--	--	19.8	--	--
Trial Mean	66	16,194	28	17	59.1	18.4	47.6	43.3	17.9	--	--
CV %	1.5	3.8	3.8	6.8	0.9	2.1	8.1	7.6	20.9	--	--
LSD 0.05	1	861	1.5	2	0.7	0.6	5.4	4.6	5.2	--	--
LSD 0.10	1	721	1.2	1	0.6	0.5	4.5	3.8	4.4	--	--

Planting Date: April 19, 2021
Harvest Date: August 3, 2021
Protein adjusted to 12% moisture
Previous Crop: Oat Hay
Seeding Rate: 1.2 million live seeds/ac

2021 Glen Ullin Spring Wheat - Recrop

Dickinson, ND

					--------- Grain Yield---------			Average Yield	
Variety	Seeds per Pound	KWT	Test Weight	Protein	2018*	2020	2021	2 Year	3 Year
		g/1000	lbs/bu	%	----------bu/ac----------			----bu/ac----	
CP 3915	14,026	32.4	61.9	14.0	--	51.1	41.2	46.1	--
Dagmar	14,254	31.8	61.6	13.5	--	--	39.8	--	--
Driver	14,099	32.2	62.1	14.2	--	50.9	40.9	45.9	--
Dyna-Gro Ballistic	13,908	32.7	62.4	14.2	--	--	39.1	--	--
LCS Buster	14,419	31.5	62.1	14.1	--	--	41.5	--	--
Lanning	14,157	32.2	61.8	13.8	--	46.1	41.2	43.7	--
MN Washburn	13,793	33.0	61.6	13.6	--	49.5	43.5	46.5	--
MN-Torgy	13,975	32.6	61.7	14.3	--	57.7	39.2	48.5	--
MS Ranchero	13,422	34.0	61.1	13.8	--	--	43.1	--	--
ND Frohberg	14,325	31.7	61.7	14.2	--	47.0	40.4	43.7	--
ND VitPro	14,345	31.7	61.6	14.3	71.5	43.6	39.4	41.5	51.5
SY Longmire	14,084	32.3	60.8	12.7	--	48.9	44.7	46.8	--
Trial Mean	14,067	32.3	61.7	13.9	75.0	48.1	41.2	--	--
CV %	5.8	6.0	1.7	6.2	6.6	8.1	8.2	--	--
LSD 0.05	1,168	2.8	1.5	1.2	7.1	5.6	4.9	--	--
LSD 0.10	971	2.3	1.2	1.0	5.9	4.6	4.1	--	--

Planting Date: April 27, 2021

Harvest Date: August 11, 2021

Seeding Rate: 1.2 million live seeds/ac

2019 Crop was lost due to hail

2021 Winter Wheat - Recrop Dickinson, ND

			Seeds					--------- Grain Yield---------			Average Yield	
Variety	Winter Survival	Heading Date	per Pound	KWT (g/1000)	Plant Height	Test Weight	Protein	2019	2020	2021	2 Year	3 Year
		Julian			in	lbs/bu	%	-----bu/ac-----			bu/ac	bu/ac
AAC-Wildfire	77	173	16,615	27.3	20	55.9	16.4	--	51.8	21.9	36.9	--
AC Emerson	73	169	18,606	24.4	20	57.4	16.2	45.2	38.0	17.4	27.7	33.5
CP7017AX	72	167	17,076	26.6	18	56.1	13.9	--	--	17.0	--	--
CP7050AX	78	163	18,303	24.8	18	57.8	14.5	--	--	12.1	--	--
Draper	72	167	18,179	25.0	19	56.4	14.8	--	--	19.8	--	--
Ideal	72	168	17,165	26.4	20	56.7	15.3	49.6	45.5	18.8	32.1	37.9
Jerry	60	170	15,915	28.5	20	56.6	15.6	46.7	45.1	21.2	33.1	37.7
Keldin	68	170	14,482	31.4	21	57.0	15.4	53.9	38.2	22.1	30.1	38.0
MS Iceman	48	170	17,176	26.4	19	60.2	15.3	--	--	13.9	--	--
ND Noreen	70	170	14,594	31.1	22	59.8	15.5	48.9	44.6	22.6	33.6	38.7
NE14696	67	168	15,670	29.0	21	57.1	15.1	--	40.5	22.8	31.6	--
NNH17612	58	166	16,978	26.7	18	58.8	15.2	--	--	15.3	--	--
Northern	77	171	16,389	27.7	20	58.0	15.4	54.0	44.3	25.5	34.9	41.3
Ray	68	174	14,947	30.4	22	57.0	15.8	--	--	22.3	--	--
SD Andes	73	167	15,750	28.9	19	57.8	15.2	--	--	26.4	--	--
SY Monument	70	168	17,679	25.7	19	53.9	14.3	54.9	41.0	20.8	30.9	38.9
SY Wolf	52	168	17,141	26.5	18	58.1	15.3	60.4	42.1	12.9	27.5	38.5
SY Wolverine	45	168	16,805	27.0	19	57.2	14.8	--	40.5	12.6	26.5	--
TCG Boomlock	57	169	17,637	25.7	19	57.3	15.3	53.2	42.6	19.6	31.1	38.5
WB4309	53	167	17,330	26.2	19	56.6	15.0	--	--	16.0	--	--
WB4462	70	167	16,118	28.2	18	54.5	14.9	55.2	39.6	18.5	29.0	37.7
Winner	75	167	15,801	28.7	19	56.9	14.5	--	--	23.2	--	--
Trial Mean	67	169	16,634	27.4	19	57.0	15.2	53.0	42.9	19.3	--	--
CV %	20.8	0.5	3.4	3.5	6.7	1.5	2.5	8.5	8.1	18.1	--	--
LSD 0.05	23	1	937	1.6	2	1.4	0.6	6.4	4.9	5.7	--	--
LSD 0.10	19	1	782	1.3	2	1.2	0.5	5.3	4.1	4.8	--	--

Planting Date: September 18, 2020
Harvest Date: August 2, 2021
Protein adjusted to 12% moisture
Previous Crop: oat hay
Seeding Rate: 1 million live seeds/ac

2021 Durum - Recrop Dickinson, ND

Variety	Days to Head	Seeds per Pound	Plant Height	Test Weight	KWT	Protein	Grain Yield 2019	Grain Yield 2020	Grain Yield 2021	Average Yield 2 Year	Average Yield 3 Year
			in	lbs/bu	g/1000	%	bu/ac			bu/ac	
AC Commander	65	12,850	16	58.6	35.4	18.8	53.6	39.2	12.0	25.6	34.9
Alkabo	66	12,821	17	59.3	35.5	17.1	46.8	39.4	13.9	26.7	33.4
Alzada	63	11,740	18	58.9	38.7	16.5	50.2	35.4	13.4	24.4	33.0
Ben	66	13,265	19	58.7	34.5	18.7	52.7	36.1	11.1	23.6	33.3
CDC Verona	68	12,228	19	58.1	37.2	20.0	49.7	41.7	8.0	24.9	33.1
Carpio	68	13,048	20	57.1	34.8	18.4	47.0	36.4	12.9	24.7	32.1
Divide	67	13,241	19	58.5	34.3	18.4	49.7	38.3	12.4	25.3	33.4
Grenora	66	13,072	18	59.1	34.8	17.8	51.5	39.5	14.8	27.1	35.3
Joppa	67	13,008	18	59.3	34.9	17.3	51.0	41.5	11.5	26.5	34.7
Lebsock	65	13,477	19	59.3	33.8	16.9	53.9	38.0	16.6	27.3	36.2
Maier	66	13,510	19	58.6	33.6	19.4	47.7	35.1	13.5	24.3	32.1
Mountrail	67	13,633	17	58.1	33.4	18.2	52.1	40.9	11.4	26.1	34.8
ND Grano	68	13,792	18	58.6	32.9	18.5	53.9	38.7	11.3	25.0	34.6
ND Riveland	67	11,816	20	59.2	38.4	17.1	45.8	38.3	15.3	26.8	33.1
ND Stanley	66	12,393	18	60.0	36.6	18.2	52.7	40.0	13.8	26.9	35.5
Pierce	66	13,434	20	59.1	33.9	17.7	47.2	37.8	13.3	25.6	32.8
Rugby	67	14,275	20	59.1	31.8	17.6	44.5	36.9	12.7	24.8	31.4
Strongfield	67	12,545	19	58.1	36.2	20.6	49.8	36.2	9.9	23.0	32.0
TCG-Bright	66	13,093	18	58.9	34.7	18.2	--	--	14.5	--	--
TCG-Webster	62	13,736	18	59.3	33.2	15.6	--	--	16.1	--	--
Tioga	66	12,348	19	59.4	36.8	18.3	52.1	37.6	15.3	26.5	35.0
VT Peak	66	12,662	19	59.8	35.8	18.1	50.5	37.7	11.6	24.7	33.3
Trial Mean	66	12,826	18	59.0	35.5	18.1	51.1	37.9	12.7	--	--
CV %	1.3	4.6	8.2	0.8	4.4	2.5	9.3	7.4	19.0	--	--
LSD 0.05	1	825	2	0.7	2.2	0.6	6.6	4.0	3.4	--	--
LSD 0.10	1	691	2	0.5	1.8	0.5	5.6	3.3	2.8	--	--

Planting Date: April 21, 2021
Harvest Date: August 5, 2021
Previous Crop: Oat Hay
Seeding Rate: 1.2 million live seeds/ac

2021 Barley - Recrop Dickinson, ND

Variety	Days to Head	Seeds per Pound	Plant Height	Test Weight	KWT	Protein	% Plump	------- Grain Yield--------			Average Yield	
								2019	2020	2021	2 Year	3 Year
			in	lbs/bu	g/1000	%	>6/64	----------bu/ac---------			----bu/ac----	
Six Row												
Tradition	68	15,798	16	44.5	28.7	17.2	48	67.3	40.7	22.2	31.4	43.4
Two Row												
AAC Connect	71	12,019	16	48.0	37.8	18.2	72	73.7	49.5	10.9	30.2	44.7
AAC Synergy	71	12,511	18	48.5	36.3	17.5	82	73.8	50.3	11.4	30.8	45.2
ABI Cardinal	72	13,291	16	48.7	34.2	18.9	74	74.7	52.7	12.3	32.5	46.5
Brewski	70	12,775	18	46.7	35.6	16.2	63	--	50.6	23.8	37.2	--
CDC Bow	73	12,481	17	48.5	36.4	17.1	90	--	47.7	11.3	29.5	--
CDC Fraser	72	12,193	16	47.4	37.2	17.3	91	--	--	9.2	--	--
Conlon	68	12,145	16	46.5	37.4	17.4	86	60.7	45.7	21.5	33.6	42.6
Explorer	70	13,813	16	45.8	32.9	18.5	64	86.9	52.4	20.1	36.3	53.2
MS-21B2	71	13,148	17	47.2	34.6	19.5	55	--	--	14.4	--	--
ND Genesis	69	13,403	17	46.3	34.0	15.2	60	69.1	50.5	19.2	34.8	46.3
Pinnacle	69	12,930	16	49.0	35.1	16.3	82	76.4	49.2	22.0	35.6	49.2
Trial Mean	70	13,013	16	47.3	35.1	16.7	74	73.0	48.7	18.9	--	--
CV %	1.3	4.8	4.8	1.5	4.6	2.6	12.1	11.3	7.2	13.1	--	--
LSD 0.05	1	876	1	1.0	2.3	0.6	12	11.8	5.0	3.5	--	--
LSD 0.10	1	731	1	0.9	1.9	0.5	11	9.8	4.2	2.9	--	--

Planting Date: April 21, 2021
Harvest Date: August 2, 2021
Previous Crop: Oat Hay
Seeding Rate: 1.2 million live seeds/ac
Grain protein percentages reported on a 0% moisture basis
The trial sustained extreme drought (6.69" total precipitation)

2021 Glen Ullin Barley - Recrop **Dickinson, ND**

Variety	Seeds per Pound	KWT	Test Weight	% Plump	Protein	------Grain Yield------ 2018	2020	2021	Average Yield 2 Year	3 Year
		g/1000	lbs/bu	>6/64	%	--------bu/ac--------			----bu/ac----	
Six Row										
Tradition	11,975	37.9	49.5	96	13.3	106.3	76.1	65.5	70.8	82.6
Two Row										
AAC Synergy	9,963	45.5	50.2	97	13.7	--	106.8	74.6	90.7	--
ABI Cardinal	10,443	43.4	49.6	97	13.6			80.6		
Brewski	9,636	47.1	49.6	97	12.9			69.6		
CDC Bow	10,152	44.7	49.8	97	14.0	--	94.5	65.9	80.2	--
ND Genesis	10,144	44.7	49.6	97	11.6	115.8	102.8	72.0	87.4	96.9
Trial Mean	10,240	44.5	49.7	96	12.7	117.9	95.4	69.1	--	--
CV %	3.4	3.3	1.0	1.3	4.3	9.2	7.6	11.3	--	--
LSD 0.05	508	2.2	0.8	2	0.8	16.3	10.8	11.5	--	--
LSD 0.10	420	1.8	0.6	2	0.7	13.4	9.9	9.5	--	--

Planting Date: April 27, 2021
Harvest Date: August 11, 2021
2019 Crop lost due to hail
Seeding Rate: 1.2 million live seeds/ac
Grain protein percentages reported on a 0% moisture basis

2021 Oat - Recrop

Dickinson, ND

						--------- Grain Yield---------			Average Yield	
Variety	Days to Head	Seeds per Pound	KWT	Plant Height	Test Weight	2019	2020	2021	2 Year	3 Year
			g/1000	in	lbs/bu	----------bu/ac----------			----bu/ac----	
Beach	68	14,553	31.2	24	37.1	108.5	90.3	18.4	54.4	72.4
CDC Minstrel	69	14,576	31.2	22	36.7	127.5	93.9	18.3	56.1	79.9
Cs Camden	71	13,991	32.5	19	30.9	102.4	98.5	15.3	56.9	72.1
Deon	70	15,616	29.1	20	35.8	149.8	94.5	18.5	56.5	87.6
Hayden	69	14,378	31.6	22	36.4	129.5	93.2	22.0	57.6	81.5
HiFi	70	15,622	29.1	21	32.0	118.0	93.3	13.6	53.5	75.0
Hytest	69	15,881	28.7	23	36.2	90.5	86.9	19.1	53.0	65.5
Jury	68	14,909	30.5	23	34.6	122.6	93.6	27.5	60.5	81.2
Killdeer	69	16,905	26.9	19	34.6	125.7	102.5	21.7	62.1	83.3
Leggett	70	16,017	28.4	19	36.4	97.9	88.5	15.6	52.0	67.3
ND Heart	68	13,985	32.5	24	33.9	99.2	93.0	25.1	59.1	72.4
Newburg	72	15,410	29.5	18	34.3	107.5	101.3	16.0	58.6	74.9
Otana	70	16,823	27.0	22	33.8	108.0	94.5	17.0	55.7	73.2
Paul	71	18,039	25.3	23	42.1	87.5	62.3	9.5	35.9	53.1
Rockford	70	16,322	27.9	21	35.3	123.4	90.5	17.1	53.8	77.0
Warrior	68	15,295	29.7	21	35.5	97.0	91.6	22.1	56.9	70.2
Trial Mean	69	15,138	30.2	21	35.5	113.7	91.3	20.2	--	--
CV %	1.7	4.7	4.6	8.6	4.2	14.6	7.9	30.5	--	--
LSD 0.05	2	989	1.9	3	2.1	23.2	10.1	8.6	--	--
LSD 0.10	1	827	1.6	2	1.7	19.4	8.4	7.2	--	--

Planting Date: April 19, 2021
Harvest Date: August 10, 2021
Previous Crop: Oat hay
Seeding Rate: 1 million live seeds/ac
The trial sustained extreme drought (6.69" total precipitation)

2021 Field Pea - Recrop **Dickinson, ND**

Variety	Days to Flower	Days to Mature	1000 Seed Weight	Seeds per Pound	Plant Height	Test Weight	Protein	--Grain Yield-- 2019	2020	2021	Average Yield 2 Year	3 Year
			gm		in	lbs/bu	%	--------bu/ac--------			--bu/ac--	
Yellow Types												
AAC Carver	60	92	242	1,890	16	63.6	27.6	47.0	24.2	18.6	21.4	29.9
AAC Chrome	63	93	268	1,701	14	65.0	27.4	50.1	26.1	13.8	20.0	30.0
AAC Julius	62	92	243	1,871	15	64.4	28.5	--	--	15.5	--	--
Agassiz	62	93	250	1,818	15	64.3	28.6	52.2	24.4	14.8	19.6	30.5
CDC Amarillo	63	93	218	2,088	17	63.5	29.0	43.2	34.5	14.0	24.2	30.6
CDC Inca	63	93	221	2,053	19	63.8	29.4	54.4	29.2	16.3	22.8	33.3
CDC Spectrum	62	93	253	1,794	13	63.6	29.1	45.8	29.5	15.1	22.3	30.1
Cronos	59	93	266	1,706	17	64.0	30.8	--	21.8	11.1	16.4	--
DL GrowPro	60	93	303	1,513	17	64.1	30.3	--	--	14.6	--	--
DS Admiral	60	92	247	1,849	17	63.1	30.1	40.7	30.4	16.3	23.4	29.2
Durwood	61	93	254	1,802	16	63.3	29.5	--	31.7	14.3	23.0	--
EP_6360	61	92	244	1,878	16	61.9	31.3	--	--	12.0	--	--
EP_6381	61	93	246	1,846	15	64.2	29.7	--	--	11.9	--	--
EP_6816	61	92	222	2,046	17	62.7	30.9	--	--	13.2	--	--
EP_8272	61	93	249	1,829	14	63.4	30.2	--	--	10.5	--	--
EP_8506	61	93	225	2,025	17	63.8	30.9	--	--	12.5	--	--
EP_8971	61	93	264	1,716	17	64.6	32.9	--	--	12.2	--	--
Empire	63	93	233	1,954	19	64.9	29.1	--	--	9.9	--	--
Goldenwood	68	93	204	2,230	12	65.0	29.1	--	--	11.4	--	--
Hyline	62	92	267	1,709	18	63.4	28.6	48.7	34.1	18.0	26.1	33.6
Jetset	61	92	247	1,842	19	63.2	29.8	43.6	31.1	17.2	24.1	30.6
MS-20YP4	63	93	242	1,895	16	64.4	29.4	--	--	16.1	--	--
ND Dawn	62	93	266	1,723	16	62.8	27.7	41.8	25.8	16.1	21.0	27.9
Pizzaz	58	90	274	1,658	14	63.5	28.5	--	--	12.9	--	--
Pro 143-6220	62	92	240	1,905	15	62.3	29.0	--	--	15.8	--	--
Pro 143-6230	60	91	226	2,019	15	62.7	28.9	--	--	14.2	--	--

Pro 153-7409	60	90	246	1,844	15	61.7	28.9	--	--	15.1	--	--
Pro 174-7148	63	91	215	2,109	13	63.2	28.3	--	--	20.3	--	--
Salamanca	61	92	259	1,757	14	62.9	29.2	45.5	25.7	15.1	20.4	28.8
Spider	62	93	249	1,830	15	63.7	29.4	--	--	11.1	--	--
Green Types												
Aragorn	59	88	215	2,116	14	60.8	29.1	--	23.4	11.4	17.4	--
Arcadia	61	90	207	2,207	13	63.1	27.9	44.3	33.6	14.8	24.2	30.9
CDC Greenwater	63	94	269	1,692	17	63.4	29.5	41.1	34.9	13.6	24.2	29.8
CDC Striker	61	91	230	1,981	14	63.0	27.4	46.2	23.2	14.8	19.0	28.1
EPX_6186	62	93	252	1,807	16	63.8	28.9	--	--	13.8	--	--
Ginny 2	60	90	233	1,947	13	62.5	28.7	--	--	13.8	--	--
Greenwood	59	89	208	2,183	13	63.0	26.9	--	25.1	13.5	19.3	--
MS-20GP5	62	93	274	1,661	17	64.2	28.4	--	28.4	17.0	22.7	--
Pro 141-6258	59	88	222	2,050	14	61.7	29.2	--	--	15.4	--	--
Shamrock	62	93	235	1,945	16	64.4	29.0	--	32.8	13.0	22.9	--
Trial Mean	61	92	243	1,887	15	63.4	29.2	45.2	28.4	14.3	--	--
CV %	1.3	1.2	7.5	7.1	12.8	0.8	3.1	11.2	17.1	17.6	--	--
LSD 0.05	1	2	25	189	3	0.7	1.2	7.1	6.8	3.5	--	--
LSD 0.10	1	1	21	158	2	0.6	1.0	6.0	5.7	2.9	--	--

Planting Date: April 19, 2021
Harvest Date: July 26, 2021
Previous Crop: cover crop forage
Seeding Rate: 325,000 live seeds/ac
Grain protein percentages reported on 0% moisture basis

2021 Flax - Recrop Dickinson, ND

	Days	Days							Average Yield	
	to	to	Plant	Test	Oil		-- Grain Yield--		2	3
Variety	Flower	Mature	Height	Weight	Content	2019	2020	2021	Year	Year
			in	lbs/bu	%		------bu/ac------		----bu/ac----	
AAC Bright	57	91	16	52.5	43.9	13.6	20.1	13.4	16.7	15.7
AAC Marvelous	57	91	17	53.9	43.1	--	--	10.9	--	--
CDC Buryu	57	91	16	54.0	40.8	15.4	22.9	8.8	15.9	15.7
CDC Dorado	56	91	15	52.2	42.5	--	17.9	9.2	13.5	--
CDC Glass	57	91	15	52.3	41.9	13.3	19.7	8.6	14.1	13.8
CDC Neela	57	91	16	53.9	42.1	13.9	22.7	12.2	17.5	16.3
CDC Plava	57	90	15	52.9	42.3	9.9	18.4	10.1	14.3	12.8
CDC Rowland	57	92	15	53.8	41.3	--	--	10.8	--	--
Carter	57	92	17	51.8	40.5	14.7	20.0	10.4	15.2	15.0
Gold ND	57	92	18	54.1	42.4	14.1	19.1	13.4	16.3	15.5
ND Hammond	58	91	16	53.6	40.4	11.0	19.2	11.3	15.3	13.8
Omega	59	92	15	54.6	40.6	13.3	19.0	12.2	15.6	14.8
Webster	57	91	16	53.7	41.6	13.9	22.2	11.4	16.8	15.9
York	57	92	17	54.1	41.6	18.4	20.6	11.0	15.8	16.7
Trial Mean	58	92	17	53.6	41.8	14.6	21.1	11.3	--	--
CV %	1.3	0.8	6.6	1.4	1.4	15.0	10.9	24.4	--	--
LSD 0.05	1	1	2	1.2	0.9	3.6	3.7	NS	--	--
LSD 0.10	1	1	1	1.0	0.8	3.0	3.1	NS	--	--

Planting Date: April 23, 2021
Harvest Date: August 13, 2021
Previous Crop: Cover Crop
No Lodging observed
Oil content reported on 9% moisture basis
The trial sustained extreme drought (6.69" total precipitation)

2021 Industrial Hemp - Recrop Dickinson, ND

								-- Grain Yield--			Average Yield	
Variety	Plant Stand	1000 KWT	PLSE[1]	Seedling Mortality	Seeds per Pound	Test Weight	Oil Content[2]	2019	2020	2021	2 Year	3 Year
	ft^2	g	%	%		lbs/bu	%	------ lbs/ac ------			--- lbs/ac ---	
Anka	1	13.2	4	96	34,346	35.8	31.0	--	--	137	--	--
CFX-2	5	13.5	32	68	33,709	38.7	32.4	722	451	626	538.4	599.4
CRS-1	6	13.8	35	65	32,839	38.3	31.5	744	569	544	556.8	619.0
Canda	7	16.0	41	59	28,457	38.1	30.7	897	415	450	432.4	587.5
Joey	5	14.4	31	69	31,622	38.6	30.2	--	426	433	429.7	--
Katani	7	12.6	43	57	35,913	39.2	31.7	671	435	518	476.3	541.2
Vega	4	14.0	23	77	32,464	38.5	31.1	--	483	508	495.3	--
Trial Mean	4.8	13.9	30	70	32,764	38.2	31.2	697	427	459	--	--
CV %	34.3	2.6	34.3	14.7	2.5	2.1	3.1	13.8	17.3	14.7	--	--
LSD 0.05	2.4	0.5	15	15	1,239	1.2	1.5	136	108	101	--	--
LSD 0.10	2.0	0.4	13	13	1,023	1.0	1.2	114	89	83	--	--

[1] Pure live seed emergence

[2] oil content reported as is basis (uniformly dried to approximately 3% moisture)

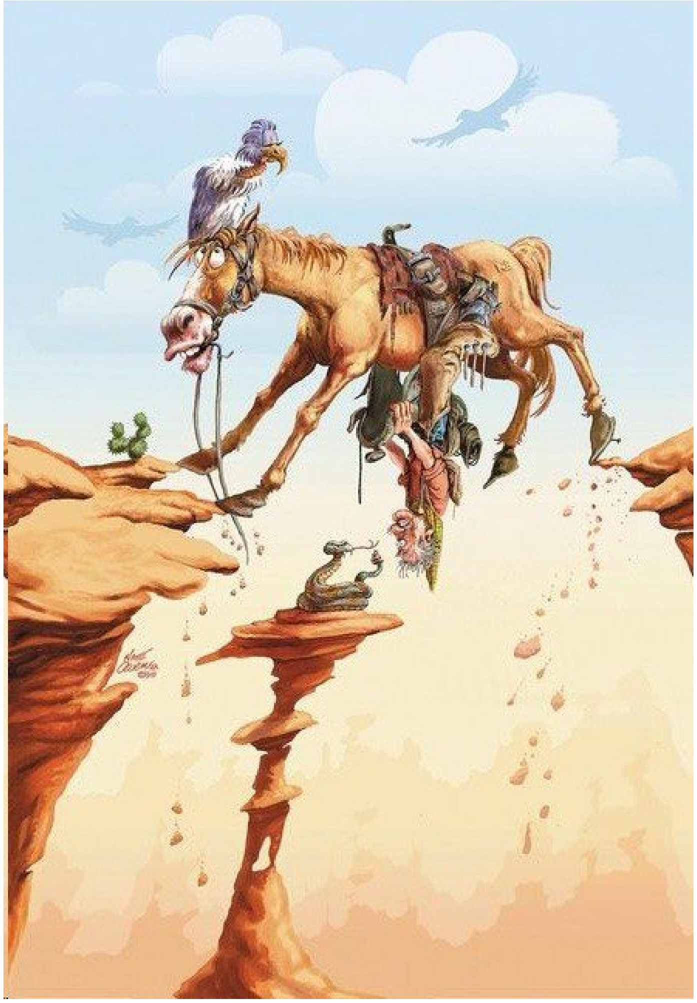
Target seeding rate was 12 seeds/ft2 + additional 25% for expected mortality loss.

Planting Date:	June 2, 2021	
Harvest Dates:	August 25, 2021	CFX-2, CRS-1, Katani
	August 30, 2021	All others

Previous Crop: cover crop forage

The trial sustained extreme drought (6.69" total precipitation)

Traditional Grassland Practices that are Not Biologically Effective



North Dakota State University
Dickinson Research Extension Center
2021

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Traditional Grassland Practices that are Not Biologically Effective

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Preface

Since the beginnings of animal agriculture, grassland management practices have usually been developed by trial and error based on simplistic aboveground concepts. A short description of six meager aboveground concepts that have been used to develop noneffective traditional management practices are listed below.

Nitrogen Fertilizer

Grassland ecosystems managed with traditional practices become degraded with a decrease in mid grasses and an increase in short grasses as a result of a deficiency in available mineral nitrogen. A simple solution appeared to be to apply nitrogen fertilizer.

Alfalfa Interseeding

Livestock grazing native grasslands managed with traditional practices had low weight gains after 1 August resulting from a deficient quantity of crude protein in mature grass lead tillers. A simple solution appeared to be to interseed alfalfa into the grasslands.

Prescribed Fire

Fire had historically been a recurrent factor on grasslands. Following settlement of the Northern Plains and the implementation of traditional practices and the suppression of fire, the degraded grasslands were occupied by increasing quantities of encroaching woody species, weedy forbs, and introduced grasses. Prescribed burning seemed to be the natural solution.

Undisturbed Treatment

Grasslands had been perceived to have several multiple equal uses as watershed, wildlife habitat, recreation, and livestock grazing. This concept assumed that if one of the uses were reduced another use could be increased. A standard undisturbed treatment developed that removed the livestock grazing use with the intent to increase wildlife, rare plants, and special interest insects.

Deferred-Rotation

Grasslands were among the last land types to be recognized as needing scientific study. At that time there were no perennial grass scientists. Agronomically trained scientists were tasked with the initial research. As a result, an early hypothesis to improve degraded grasslands was to reseed by mechanical methods. An effort to bypass this treatment was the development of the deferred-rotation grazing practice.

Weed Intrusion

Weeds were assumed to dislodge and push out the desirable plants and herbicide treatments that removed the weeds would restore the grassland ecosystem. The previously used poor traditional management practices have not been held responsible for the ecosystem degradation that permitted the intrusion of weeds.

These six concepts have been analyzed with modern scientific fundamentals for their biological effectiveness. The reasons why these concepts have not been able to properly manage complex grassland ecosystems are explained in this report.

Nitrogen Fertilization of Native Grasslands is Not A Solution to Low Soil Mineral Nitrogen

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Report DREC 20-3093

Native rangelands of the Northern Plains managed by traditional grazing practices are deficient in available mineral nitrogen which is responsible for the widespread low herbage biomass production and the below genetic potential calf weight gains per acre. A well defined problem of available mineral nitrogen deficiency would seem to be a no brainer, just apply nitrogen fertilizer, problem solved. Except decades of research tell us that this problem is not that simple.

It turns out that intact rangelands are not deficient in nitrogen. The large quantities of organic nitrogen are not available for plant use. The ecosystem biogeochemical processes are extremely complex and adding nitrogen fertilizer greatly messes with these processes and creates a new set of problems. This report will summarize four of the problems created when nitrogen fertilizer is added to native rangeland. The resulting increased herbage biomass produced has exorbitant costs. The added nitrogen fertilizer has extremely low effectiveness with only 3% to 10% of the quantity added used in the aboveground herbage. Adding nitrogen fertilizer causes a short-term plant species shift while the treatment continues and then there is a long-term plant species shift that continues for one hundred years or more after the treatment had been terminated. Livestock grazing nitrogen fertilized pastures do not improve in weight gain performance. Any one of these four created problems is severe enough on its own to invalidate the cultural practice of adding nitrogen fertilizer to native rangeland.

High Cost

The human population of the Northern Plains greatly increased during 1898 to 1915 encouraged by the Homestead Act of 1862 and followed the construction of the railroads. Title to 160 acres of surveyed public domain land west of the Mississippi River was transferred to private citizens as a provision of the Homestead Act. Several attempts to adjust the law to meet the needs of the people and natural resources were made. However, none of the many revisions of the Act met the needs of the subhumid, semiarid, and arid portions of the Northern Plains. Failure of the lawmakers to address the requirements of these dry natural resources and not providing the technology for proper grassland management caused numerous long-lasting management problems. Naive homesteaders implemented eastern grazing practices with stocking rates greater than 60% heavier than the biological carrying capacity of the grasslands west of the 20 inch rainfall line. As a result, the grassland resources deteriorated with inadequate quantities of available soil mineral nitrogen and a decrease in herbage biomass production with a disproportional reduction of mid cool season grass species, such as western wheatgrass, and leaving a predominance of short warm season grass species, such as blue grama (Whitman et al. 1943).

Heavy grazing damages grass species with long shoot tillers to a greater extend than grass species with short shoot tillers. Grass species with long shoots elevate the apical meristem a short distance above ground level by internode elongation while still in the vegetation stage (Dahl 1995) exposing the elevated apical meristem to removal by grazing prior to flowering. Grass species with short shoots do not produce significant internode elongation during vegetative growth and apical meristem remains below grazing or cutting height until the flower stalk elongates during the sexual reproductive stage (Dahl 1995). Grass species with long shoots are nearly always decreased at greater rates than grass species with short shoots in pastures that are repeatedly grazed with heavy stocking rates (Branson 1953).

The drought conditions of 1934 and 1936 greatly intensified the damaging effects of the widespread heavy overgrazing of Northern Plains grasslands. The severe damage to the grassland vegetation caused by overgrazing and drought conditions, resulted in a 57% decrease in total cover density and a 56% reduction in plant height (Whitman et al. 1943). Grasslands managed by traditional grazing practices are deficient in available soil mineral nitrogen and produce only one half to one third of the potential quantities of herbage biomass. As a result of the economic depression of the late 1920's, the severe drought conditions of the

1930's, and the lack of proper regional technology, a high proportion of homesteaders gave up on agriculture in the Northern Plains. Efforts to develop agricultural management practices suitable for the dry Northern Plains grasslands were started in the 1930's but the major projects had to be postponed until after World War II.

The scientists returning from the war were facing deteriorated grasslands with more than 50 years of inappropriate management that were in desperate need of restoration. A potential solution to these problems was the recent availability of ammonium nitrate fertilizer and the derivation of a new agricultural concept to be known as the green revolution. The stocking rate problems were solved when Crider (1955) determined that proper stocking rates should remove only about 50% of the herbage and that grass tillers with more than 50% of the aboveground leaf and stem material removed reduced root growth, root respiration, and root nutrient absorption.

Grassland scientists at the North Dakota State University Dickinson Research Extension Center conducted research projects into the potential use of nitrogen fertilization treatments to improve native rangeland ecological conditions during 48 years between 1957 and 2004 with four scientists contributing 68 scientist years to the subject.

The first plot study was on heavily grazed native range pasture with three fertilizer rates and a control replicated three times. The heavy rate of 150 lbs N/ac apparently caused damage to the grasses and was eliminated from use in future trials. The 50 lbs N/ac and 100 lbs N/ac increased herbage biomass of mid cool season grasses and decreased the percent composition of the short warm season grasses. This study showed the start of the species composition shift that scientists thought was needed to improve plant community structure. However, Whitman (1957) submitted a prediction; that based on the then current price of nitrogen fertilizer, additional benefits other than seen in this early study would be necessary to make the practice of nitrogen fertilization economically profitable, but that he did not have sufficient data yet.

The data from 17 years of plot studies during 1962 to 1978 using the fertilizer cost of $0.24 per pound of nitrogen and land rent at $8.76 per acre shows that the mean cost of unfertilized herbage was $11.59 per ton. The mean cost of herbage weight on the ammonium nitrate annually applied treatment rates of 33 lbs N/ac, 67 lbs N/ac, and 100 lbs N/ac was $62.34, $41.58, and $60.40 per ton that were 437.9%, 258.8%, and 421.1% greater than the cost of unfertilized herbage per ton, respectively (table 1). The mean total herbage weight produced on the fertilization treatment rates of 33 lbs N/ac, 67 lbs N/ac, and 100 lbs N/ac was 21.6%, 52.9%, and 57.5% greater, respectively, than the total herbage weight produced on the unfertilized treatments. These costs for herbage per ton would be for vegetation if it were cut for hay. Pasture forage cost per ton would be greater.

On native range grazinglands, about 50% of the produced herbage is required by the plants to remain healthy and productive and about 50% of the herbage is not needed by the plants and is expendable. About 50% of the expendable herbage is lost from the plant by leaf senescence and removed by insects and wildlife. The other 50% of the expendable herbage can be captured and ingested as forage by grazing livestock, which is 25% of the total herbage produced. The cost of forage weight per ton is four times greater than the cost of herbage weight per ton. The cost of forage produced on the fertilization rates of 33 lbs N/ac, 67 lbs N/ac, and 100 lbs N/ac would be $249.36, $166.32, and $241.60 per ton, respectively. These forage costs seem to be excessive and not economical as Dr. Whitman suspected.

The primary reason for the high herbage weight costs on the fertilization treatments was low pounds of herbage produced per pound of nitrogen applied. The mean weight of herbage produced per pound of nitrogen applied at the treatment rates of 33 lbs N/ac, 67 lbs N/ac, and 100 lbs N/ac was 9.10 lbs 12.23 lbs, and 8.76 lbs, respectively (table 2, figure 1).

With these few pounds of herbage produced per pound of nitrogen, each pound of herbage produced on the fertilization treatments had a substantially greater cost than the herbage produced on the unfertilized treatments. This exorbitantly high cost of herbage weight makes it unprofitable to fertilize native rangelands.

Low Effectiveness

Annual application of nitrogen fertilizer at treatment rates of 33 lbs N/ac, 67 lbs N/ac, and 100 lbs N/ac increased the total herbage biomass production an average of 22%, 53%, and 58% greater, respectively, than that produced on the unfertilized control (Whitman 1972). The percent increases are variable with different soil characteristics (Whitman 1969). The quantity of increase in herbage production for various fertilizer rates on different soil types is not linear as would be expected if the fertilizer treatment rates had equal effectiveness.

Among the three annual nitrogen rates tested, Whitman (1978) determined that the application rate of 67 lbs N/ac was the more efficient rate because it used the lowest amounts of nitrogen and the lowest amount of soil water for each pound of additional herbage produced beyond the herbage weight produced on the unfertilized treatment. The differences in effectiveness of various fertilization rates are greatly affected by the quantities of available soil water and the immobilization rates of the soil ecosystem.

Water use efficiency (pounds of herbage produced per inch of water use) increased with increased rates of available mineral nitrogen (Smika et al. 1965, Wight and Black 1972, Whitman 1976, 1978), however, at the Mandan ARS, Smika et al. (1965) found that the quantity of available soil water required for fertilizer rates greater than 40 lbs N/ac to reach maximum water use efficiency usually does not occur under natural conditions in the Northern Plains.

Not all of the applied nitrogen is available for plant growth. Only a small portion of the applied fertilizer nitrogen reaches the aboveground herbage and crowns of grass plants, which was determined by Power (1977) to be only 3%, and that most of the applied nitrogen (48% or greater) is immobilized and unavailable. At the fertilizer rate of 30 lbs N/ac Smika et al. (1961) found that 26.7 lbs N/ac was immobilized and only 3.3 lbs N/ac was incorporated into the aboveground herbage. At the fertilizer rates of 40 lbs N/ac and 60 lbs N/ac applied very early in May Manske and Goetz (1988) found that during the month after application, the quantity of nitrogen immobilized by the soil-plant system into grass roots, soil organic matter, microbial tissue, and fixed by adsorption unto clay particles was so great that during the growing season of early June to late August the amounts of mineral nitrogen available on the fertilization treatments was essentially the same as the amounts available on the unfertilized treatment (table 3).

The effectiveness of nitrogen fertilization to increase herbage weight of perennial plants in grasslands is much lower than the affects on annual plants in croplands. In croplands, nitrogen fertilizer causes great increases in the number of seeds that grow and survive to maturity producing a much larger grain crop than on unfertilized cropland. Increases in perennial grass density on grasslands does not come from seeds. Perennial grass density increases by vegetation production of tillers from axillary buds. The vegetative tiller mechanisms require a minimum of 100 lbs N/ac to be available but nitrogen fertilization does not activate the mechanisms. Some increase in herbage weight comes from about a 13% increase in leaf length of lead tillers on fertilized treatments. Some increase in herbage weight occurs when lead tillers at different phenological growth stages are synchronized by the fertilizer treatment to grow together. Some increase in herbage weight comes from existing vegetative secondary tillers to develop earlier than those on unfertilized treatment and produce leaf biomass. Most of this increase in growth comes from mid cool season grasses and occurs during June and stops between mid and late July. A high proportion of the increase in total herbage biomass comes from the increase in density and size of undesirable forbs primarily from fringed sage, white sage, and green sage, which varies by soil type. The increase in forb weight lasts for 4 to 7 or more years. The crude protein content of the synchronized lead tillers is slightly higher than the tillers on unfertilized treatments during the early portion of the growing season. The synchronized lead tillers also reach senescence with greatly reduced crude protein content much earlier than the lead tillers on unfertilized treatments. On unfertilized treatments, when the lead tillers reach maturity, the vegetative secondary tillers grow and develop providing forage during August, September, and to mid October. On fertilized treatments, when the lead tillers reach senescence early, the vegetative secondary tillers have already grown, resulting in no new growth after early August.

Fertilization treatments causes most native plant categories to perform most of the plant growth during the early portion of the growing season (May and June) with little growth during the latter portion of the growing season (July and August). Table 4 shows the fertilization treatments of 40 lbs NEY and 60 lbs NEY causes great quantities of plant growth to occur during May and June for the cool season grasses, sedges, native grass, and total yield and causes little plant growth for those categories during July and August. The unfertilized treatment permits greater quantities of plant growth to occur during July and August for the cool season grasses, sedges, native grass, and total yield. Fertilized plants had a short period of rapid growth in herbage weight during the early portion of the growing season during May and June. Unfertilized plants had a longer period of herbage weight growth; during the early portion, the rates of growth was lower than the rates of fertilized plants, and during the latter portion of the growing season, July and August, the rate of growth in herbage weight was greater for the unfertilized plants.

Figure 2 shows the greater percent growth of cool season grasses during May and June on the 60 lbs NEY treatment and the greater percent growth during July and August on the unfertilized treatment.

The increase in herbage biomass and crude protein content only occurs during the early portion of the growing season of May, June, and may extend to mid July. During July and August the fertilized vegetation has loss of weight from accelerated early senescence resulting in decreases in crude protein. Only a small portion of the applied nitrogen fertilizer is available for aboveground grass growth in herbage weight. Most of the applied nitrogen becomes immobilized within the first month after application. As a result, only about 9 lbs to 12 lbs of herbage weight is produced per pound of applied nitrogen. Nitrogen fertilizer applied to native rangeland had low effectiveness.

Plant Species Shift

Deterioration of the ecological condition of Northern Plains mixed grass prairie communities results from naive traditional management practices with inappropriate season of use that is too early, too late, too long and/or too heavy use over a prolonged period of time (Goetz 1984). This deterioration causes a reduction in herbage biomass production and a disproportional reduction of mid cool season grass species, such as western wheatgrass, and leaving a predominance of short warm season grass species, such as blue grama. When one thing decreases faster than a second thing, the second thing has an apparent relative increase while decreasing at a slower rate than the first thing.

Grass species with long shoot tillers are damaged greater than grass species with short shoot tillers by inappropriate grazing management practices. Short shoot tillers do not elevate the apical meristem until the flower stalk elongates during the flowering stage. Long shoot tillers elevate the apical meristem above grazing height while still in vegetative growth stage (Dahl 1995).

Nitrogen fertilizer annually applied during early spring in early April to very early May or applied during fall in mid October results in a short term plant species shift of an increase in mid cool season grasses (western wheatgrass) and a decrease of short warm season grasses (blue grama). This shift in plant species composition was, at first, considered to be a beneficial change that restored the natural balance in the botanical species composition to the deteriorated Northern Plains mixed grass prairie.

With intuitive foresight, Goetz et al. (1978) predicted several undesirable aspects related to the changes in plant species composition that have implications of adverse consequences for mixed grass prairie communities. Detrimental complications could develop from synthetically induced changes in plant species because the increasing mid cool season grasses were primarily single stalked, low-cover, plants and the decreasing short warm season grasses were primarily multiple stemmed, high-cover, plants and the shift in plant species would cause a decrease in basal cover and a reduction in live plant material covering the soil and would open an otherwise closed community. The resulting reduction in ground cover would expose greater amounts of soil to erosion and to higher levels of solar radiation that would increase soil temperature and water evaporation. The combination of problems would create larger areas of open spaces available for potential invasion by undesirable perennial forbs, domesticated cool season grasses, and introduced annual and perennial grasses.

Taylor (1976) conducted a study for 15 years and found that residual effects from nitrogen fertilization of native rangeland were still occurring 12 years after the treatments had stopped. No other nitrogen fertilization study had studied the effect on plant species composition after the treatments had been terminated.

This current project will follow the changes in plant species composition during 35 years from 1970 to 2004 with 13 years of annual application of nitrogen with 9 years on the plot study and 11 years on the pasture study with 7 years overlapping and 22 years after application had stopped.

Evaluation of short-term and long-term changes in plant species composition complied data from 3 studies that were located at the same site on SW ¼, sec. 23, T. 140 N., R. 97W. with strongly rolling upland mixed grass prairie on Vebar, Parshall, and Flasher fine sandy loam soils. A plot study with unfertilized and annual applied 67 lbs N/ac treatments was conducted from 1970 to 1978. A pasture study with unfertilized and annual applied 50 lbs N/ac treatments was conducted from 1972 to 1982. A followup study on the pasture study treatments with unfertilized and fertilized pastures with nitrogen last applied in 1982 was conducted from 1997 to 2004. Aboveground herbage biomass was sampled by hand clipping to ground level during peak biomass in mid July to mid August. Herbage was separated into four categories during the 1970 to 1978 and separated into five categories during 1982 to 2004. Plant species composition was determined by percent basal cover sampled with the ten pin point frame with 1500 points per treatment during mid July to mid August.

During the 13 years with annual nitrogen fertilization application, the total herbage weight progressively increased with 37.8%, 39.4%, 50.6%, and 91.4% greater than the total herbage weight on the unfertilized treatment during years 1, 3, 9, and 11, respectively (table 5). During the 22 years after fertilizer application had been terminated, the total herbage weight decreased on the area that had been fertilized but was still 44.1% and 48.9% greater than the total herbage weight on the unfertilized treatment during years 27 and 31, respectively (table 5). Total basal cover on the fertilized treatments had decreased 21.5%, 23.4%, 41.5%, and 24.9% lower than that on the unfertilized treatments during years 7, 11, 27, and 31, respectively (table 6).

Warm season grass herbage weight of the fertilized treatment increased 42.0% during year 1 than greatly decreased 33.0%, 69.0%, 71.5%, 89.7%, and 86.2% during years 3, 9, 11, 27, and 31, respectively (table 5). Basal cover of warm season grass decreased on the fertilized treatment 67.1%, 67.8%, 72.8%, and 64.4% during years 7, 11, 27, and 31, respectively (table 6).

Cool season grass herbage weight of the fertilized treatment increased 7.5%, 85.7%, 89.9%, and 166.4% during years 1, 3, 9, and 11 when fertilizer was applied then decreased 70.1% and 83.3% during years 27 and 31 when application of fertilizer had been terminated, respectively (table 5). Cool season grass basal cover on the fertilized treatment increased 14.9% and 40.3% during years 7 and 11 when fertilizer was applied then decreased 72.6% and 79.4% during years 27 and 31 after fertilization had been terminated, respectively (table 6).

Forb herbage weight, primarily was fringed sage, on the fertilized treatment increased 150.3%, 65.6%, 8.4%, and 70.0% during years 1, 3, 9, and 11 when fertilizer was applied then decreased 66.0% and 58.1% during years 27 and 31 after fertilization had been terminated, respectively (table 5). Forb basal cover on the fertilized treatment increased 66.4% during year 7 then decreased 75.7%, 62.9%, and 67.7% during years 11, 27, and 31, respectively (table 6).

Upland sedge herbage weight had small quantities and did not have a separate category until year 11 (1982). It most likely changed little on the fertilized treatment during the early years. Upland sedge herbage weight on the fertilized treatment decreased 16.0%, 33.2%, and 59.4% during years 11, 27, and 31, respectively (table 5). Upland sedge basal cover on the fertilized treatment increased 1.2% during year 7 then decreased 14.2%, 22.2%, and 53.7% during years 11, 27, and 31, respectively (table 6).

Domesticated grass herbage biomass was not collected on the unfertilized treatment until year 31 with 31.87 lbs/ac. Domesticated grass herbage biomass was collected as a separate category for the first time during year 11 (1982) with 517.05 lbs/ac. This was the last year of fertilizer application. This small quantity of domesticated grass intrusion on the fertilized treatment was not recognized as a serious problem. Domesticated grass herbage weight on the fertilized treatment was produced at 1551.84 lbs/ac during year 31 with an increase of 200.1% in 20 years (table 5). During year 31, native grass herbage weight was 13.25% composition and domesticated grass herbage weight was 82.67% composition of total herbage weight.

Domesticated grass basal cover on the fertilized treatment was 988.9%, 444.4%, 299.2%, and 356.1% greater than that on the unfertilized treatment during years 7, 11, 27, and 31, respectively (table 6). The domesticated grass category was comprised of crested wheatgrass, smooth bromegrass, Kentucky bluegrass, and Canada bluegrass. Basal cover on the fertilized treatment during year 11 was 0.67, 0.63, and 0.66 for crested wheatgrass, smooth bromegrass, and the two bluegrasses. In twenty years, during year 31, basal cover on the fertilized treatment had increased 616.4%, 606.4%, and 483.3% for crested wheatgrass, smooth bromegrass, and the two bluegrasses, respectively.

During the twenty years after the nitrogen fertilization treatments had been terminated, the residual effects from the nitrogen applications continued to change the native rangeland plant species composition. Warm season grass herbage weight had decreased 86.2%, and basal cover had decreased 64.4%. Cool season grass herbage weight had decreased 83.3%, and basal cover had decreased 79.4%. Upland sedge herbage weight had decreased 59.4%, and basal cover had decreased 53.7%. Forb herbage weight had decreased 58.1%, and basal cover had decreased 67.7%. Domesticated grass herbage weight had increased 4769.3%, and basal cover had increased 356.1%. Total herbage weight had increased 48.9%, and total basal cover had decreased 24.9% (tables 5 and 6).

In a 31 year period consisting of eleven years of annual application of nitrogen fertilizer on native mixed grass prairie and twenty years following cessation of nitrogen application, the prairie community dominated with western wheatgrass, needle and thread, blue grama, and threadleaf sedge shifted in plant species composition to a community dominated with crested wheatgrass, smooth bromegrass, Kentucky bluegrass, and Canada bluegrass. This large plant species shift in composition was exactly the change hypothesized to occur by Goetz et al. 1978.

This negative residual effects from nitrogen fertilization on native rangeland will continue as long as fertilizer nitrogen remains in the ecosystem. Power (1977) determined that 8% or 4.0 lbs N/ac of the applied nitrogen was lost or removed from the ecosystem per year. During 11 years with annual application, a total of 550 lbs N/ac was applied. During the first 11 years, 44 lbs N/ac would have been removed and during the next twenty years, 80 lbs N/ac would have been removed, with a quantity of 426 lbs N/ac remaining in the ecosystem. At a removal rate of 4.0 lbs N/ac per year, the ecosystem should be devoid of nitrogen fertilizer sometime during the growing season in the year 2109.

Application of nitrogen fertilizer to native rangeland is no longer considered to be a viable cultural practice for restoration of degraded ecosystems.

Livestock Performance Not Improved

Nitrogen fertilization of native rangeland increased total herbage weight and increased aboveground herbage crude protein content, as a result it would seem logical that livestock grazing fertilized native rangeland pastures would improve in weight performance. Unfortunately, the herbage weight and crude protein increases only occur during the early portion of the growing season in May and June and lasting sometimes into mid July. After that, the fertilized forage is in advanced stages of senescence.

During 1982, nitrogen fertilizer was applied for the eleventh and last time on the pasture study. A comparison of herbage growth on fertilized and unfertilized treatments is shown in table 7. Generally, the fertilized plants have greater herbage growth during a short period in the early portion of the growing season. The unfertilized plants have active growth during about double the length of time of the fertilized plants and have greater herbage growth during the latter portion. Greater percent senescence occurred on the fertilized pasture during the latter portion of the growing season.

The cool season grasses on the unfertilized and fertilized pastures gained herbage weight during May to mid July. The fertilized cool season grasses lost 42.8% of the herbage weight during August and September. The unfertilized cool season grasses decreased 26.6% of the herbage weight during August and September (table 7).

The warm season grasses on the unfertilized pasture had 126.4% greater herbage weight during mid July than that of the fertilized pasture. The fertilized warm season grasses lost 59.1% of the herbage weight during August and September. The unfertilized warm season grasses continued to gain 85.6% in herbage weight in mid August (table 7).

The unfertilized pasture did not have an introduced grass component. The fertilized pasture total herbage weight comprised of 18.4% introduced grass during mid July which rapidly senesced during August (table 7). The fertilized pasture had little green growing forage after mid July.

Most grass species on the fertilized pasture attained maximum crude protein in mid May, were not different from grasses on the unfertilized pasture during mid June to early July, and were below livestock requirements in early August.

Steers grazed the unfertilized and fertilized pastures during 1972 to 1976. The steer weight gains were slightly greater on the fertilized pasture but not significantly different than those on the unfertilized pasture (table 8). Steer gain per head was 5.6% greater. Steer gain per day was 7.9% greater. Steer gain per acre was 58.6% greater.

Steers gain per day on the fertilized pasture was 19.3% greater during the early portion of the growing season from mid June to late July. Steer gain per day on the unfertilized pasture was 16.4% greater during the latter portion from early August to mid September (table 9).

Steers on the fertilized pasture used 32.4% less land area but had 64.0% greater pasture costs. Steers on the fertilized pasture gained 5.6% greater weight. But because of the lower pasture costs, steers on the unfertilized pasture had 23.7% greater net returns per head (table 10).

Cow-calf pairs grazed the unfertilized and fertilized pastures during 1978 to 1982 minus the drought season of 1980. The cow weight gains were much greater on the unfertilized pasture but not significantly different. The calf weight gains on the unfertilized pasture were greater per head and per day and calf weight gains per acre were greater on the fertilized pasture but calf gains were not significantly different (table 11). Cow gain per head was 105.6% greater. Cow gain per day was 104.1% greater. Cow gain per acre was 109.4% greater on the unfertilized pasture. Calf gain per head was 8.4% greater. Calf gain per day was 25.2% greater on the unfertilized pasture. Calf gain per acre was 36.8% greater on the fertilized pasture.

Cow gain per day on the fertilized and unfertilized pastures was similar during the early portion from mid June to late July. Cow gains on the fertilized pasture lost greater weight during the latter portion of the growing season than they had gained during the early portion (table 12). Calf gain per day on the unfertilized pasture was 5.0% greater during the early portion and was 93.7% greater during the latter portion (table 12).

Cow-calf pairs on the fertilized pasture used 32.8% less land area but had 63.3% greater pasture costs. Calves on the unfertilized pasture gained 8.4% greater weight, but because of the lower pasture costs, calves weight produced 52.4% greater net return per cow-calf pair. Calves on the unfertilized pasture had 46.2% lower cost per pound gained (table 13).

Steer and Cow-calf weight gains on the fertilized pasture were slightly greater or about the same as that on the unfertilized pasture during the early portion until late July. But during the latter portion livestock gains on the fertilized pasture were poor or they lost weight. Fertilized grasses grow rapidly and contain good crude protein during the early portion, then they quit growing and develop accelerated senescence.

Intact native rangeland is not low in nitrogen. In the Northern Plains, rangelands contain about 6 to 8 tons of organic nitrogen which is not available for plant growth. Organic nitrogen must be mineralized by soil microorganisms in order to make the nitrogen available to plants. Rangelands managed by traditional or gimmicky grazing practices have low microorganism biomass. Rangelands with a deficiency in available mineral nitrogen is not deficient in nitrogen but deficient in adequate biomass of soil microorganisms.

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I am grateful to Sheri Schneider for assistance in the production of this manuscript and for development of the tables and figures.

Table 1. Cost of herbage weight per ton on annual ammonium nitrate fertilization treatments and on unfertilized treatments, 1962-1978.

	Treatment Rates			
Study Sites	0 lbs N/ac $/ton	33 lbs N/ac $/ton	67 lbs N/ac $/ton	100 lbs N/ac $/ton
Annual Treatments				
Creek terrace site	11.52	38.49	34.99	52.72
Upland slope site	12.90	33.92	36.75	53.22
Havre overflow range site	6.97	112.21	37.67	84.98
Manning silty range site	11.42	75.55	34.07	34.89
Vebar sandy range site	13.16	47.40	33.66	48.03
Rhoades thin claypan range site	17.33	66.44	69.49	93.57
Upland range site	7.81	-	44.46	55.38
Mean	11.59	62.34	41.58	60.40
Difference %		437.88	258.76	421.14

Table 2. Herbage weight in pounds per acre per pound of nitrogen fertilizer applied, 1962-1978.

	Nitrogen Fertilization Rates		
Study Sites	33 lbs N/ac	67 lbs N/ac	100 lbs N/ac
Creek terrace site	12.47	13.72	9.11
Upland slope site	14.15	13.06	9.02
Havre overflow range site	4.28	12.74	5.65
Manning silty range site	6.35	14.09	13.76
Vebar sandy range site	10.13	14.26	9.99
Rhoades thin claypan range site	7.22	6.91	5.13
Upland range site	-	10.80	8.67
Mean lbs herbage/lb nitrogen	9.10	12.23	8.76

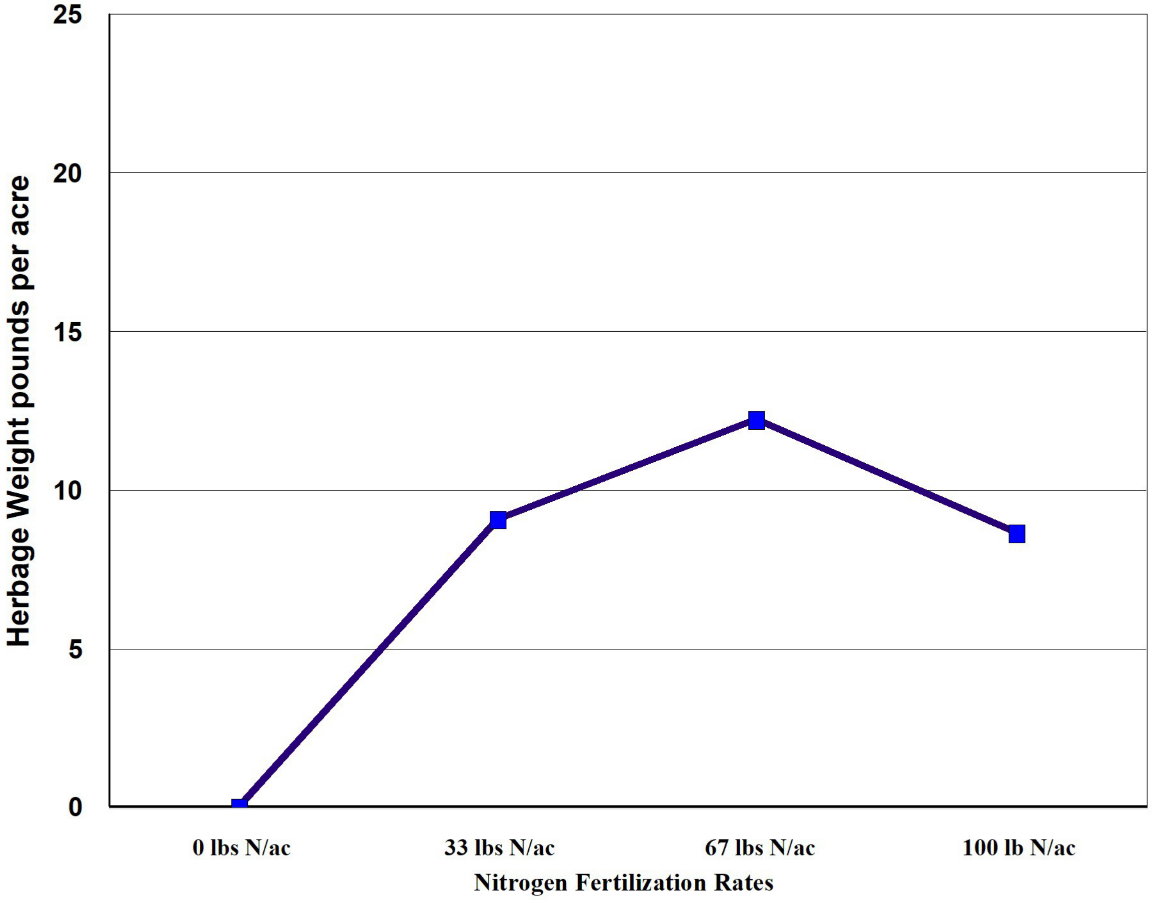

Figure 1. Herbage weight in pounds per acre per pound nitrogen fertilizer applied.

Table 3. Mean soil mineral nitrogen content in pounds per acre for fertilization treatments on the Moreau clayey range site, 1982-1985.

	Soil Depth in inches					
Treatments	0-6	6-12	12-24	24-36	36-48	0-48
Inches of Soil Water	0.96	0.86	1.62	1.61	1.66	6.71
Unfertilized	8.34ab	7.05a	12.77ab	15.84ab	17.62a	61.61a
Ammonium nitrate						
40 lbs N EY	9.77ab	7.03a	13.64ab	15.36ab	15.62a	61.41a
60 lbs N EY	15.21b	9.09a	13.82a	13.78ab	13.47a	65.37a

Means in the same column and followed by the same letter are not significantly different ($P<0.05$).

Table 4. Percent herbage growth and senescence of plant categories for fertilization treatments on the Moreau clayey range site, 1982-1985.

Dates Treatments	Cool Season	Warm Season	Sedge	Total Native Grass	Forbs	Total Yield
Unfertilized						
30 May	52.00	46.80	83.17	55.48	51.02	54.71
23 Jun	21.51	15.62	-17.81	15.04	22.71	16.46
23 Jul	13.46	5.25	10.76	10.74	26.27	13.60
23 Aug	13.03	32.33	6.07	18.73	-0.40	15.24
Ammonium nitrate						
40 lbs N EY						
30 May	55.28	21.11	83.63	48.67	56.51	50.90
23 Jun	37.07	18.50	-22.34	28.09	12.28	25.54
23 Jul	6.26	41.91	-6.92	15.76	31.21	18.91
23 Aug	1.40	18.48	16.37	7.49	-8.26	4.64
60 lbs N EY						
30 May	59.22	29.66	84.99	60.08	54.63	59.19
23 Jun	29.83	25.81	-12.49	25.80	13.89	23.84
23 Jul	10.95	8.49	-9.38	8.42	23.55	10.91
23 Aug	-14.31	36.04	15.01	5.69	7.94	6.06

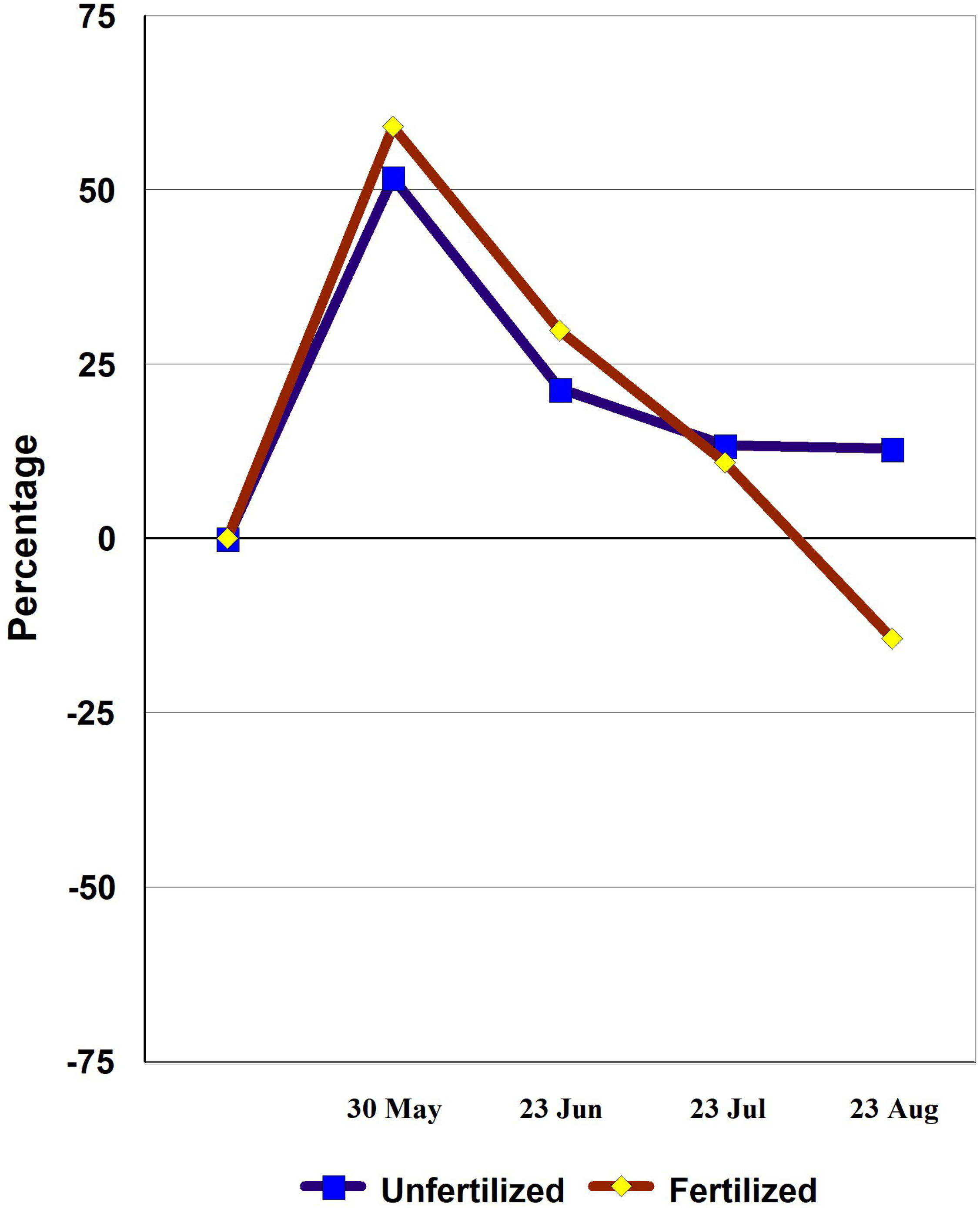

Figure 2. Percent herbage growth and senescence of cool season grasses for 60 lbs N EY and unfertilized treatments on the Moreau clayey range site, 1982-1985.

Table 5. Percent difference from fertilization treatment in herbage weight in pounds per acre on native rangeland plots and pasture on the upland range site, 1970-2004.

Year Treatment % Difference	Warm Season Short Grass	Cool Season Mid Grass	Sedge	Total Native Grass	Domesticated Grass	Forbs	Total Yield
Plot Data							
1970 Year 1							
Unfertilized lbs/ac	1078.00	905.00		1983.00		203.00	2186.00
Fertilized lbs/ac	1531.00	973.00		2504.00		508.00	3012.00
Difference %	42.02	7.51		26.27		150.25	37.79
1972 Year 3							
Unfertilized lbs/ac	1223.00	1653.00		2876.00		456.00	3332.00
Fertilized lbs/ac	819.00	3069.00		3888.00		755.00	4643.00
Difference %	-33.03	85.66		35.19		65.57	39.35
1978 Year 9							
Unfertilized lbs/ac	506.00	1874.00		2380.00		309.00	2689.00
Fertilized lbs/ac	157.00	3558.00		3715.00		335.00	4050.00
Difference %	-68.97	89.86		56.09		8.41	50.61
Pasture Data							
1982 Year 11							
Unfertilized lbs/ac	517.15	898.28	281.90	1697.33	0.00	214.27	1911.60
Fertilized lbs/ac	147.40	2392.55	236.70	2776.65	517.05	364.25	3657.95
Difference %	-71.50	166.35	-16.03	63.59	100.00	70.00	91.36
1998 Year 27							
Unfertilized lbs/ac	322.07	527.35	305.42	1154.84	0.00	230.73	1385.57
Fertilized lbs/ac	33.06	157.47	204.09	394.62	1524.01	78.50	1997.13
Difference %	-89.74	-70.14	-33.18	-65.83	100.00	-65.98	44.14
2002 Year 31							
Unfertilized lbs/ac	217.65	493.10	335.87	1046.62	31.87	182.68	1261.17
Fertilized lbs/ac	29.97	82.30	136.54	248.81	1551.84	76.59	1877.24
Difference %	-86.23	-83.31	-59.35	-76.23	4769.28	-58.07	48.85

Table 6. Percent difference from fertilization treatment in plant species basal cover for native rangeland plots (1970-1976) and for native rangeland pasture (1972-2004) on the upland range site.

Year Treatment % Difference	Warm Season Grass	Cool Season Grass	Sedge	Total Native Grass	Domesticated Grass	Forbs	Total Basal Cover
Plot Data							
1976 Year 7							
Unfertilized %	14.18	9.22	5.71	29.11	0.09	1.04	30.25
Fertilized %	4.66	10.59	5.78	21.03	0.98	1.73	23.74
Difference %	-67.14	14.86	1.23	-27.76	988.89	66.35	-21.52
Pasture Data							
1982 Year 11							
Unfertilized %	9.94	4.47	6.64	21.05	0.36	1.40	22.81
Fertilized %	3.20	6.27	5.70	15.17	1.96	0.34	17.47
Difference %	-67.81	40.27	-14.16	-27.93	444.44	-75.71	-23.41
1998 Year 27							
Unfertilized %	9.93	3.63	4.33	17.93	1.17	1.97	21.07
Fertilized %	2.70	0.85	3.37	6.92	4.67	0.73	12.32
Difference %	-72.81	-76.58	-22.17	-61.41	299.15	-62.94	-41.53
2002 Year 31							
Unfertilized %	7.00	5.81	9.77	22.58	2.87	5.10	30.55
Fertilized %	2.48	1.20	4.52	8.20	13.09	1.65	22.94
Difference %	-64.43	-79.35	-53.74	-63.68	356.10	-67.65	-24.91

Table 7. Monthly dry matter weight in pounds per acre for treatments on the evaluation of native rangeland pasture fertilization trial, 1982.

Plant Categories Treatments	15 May	15 Jun	15 Jul	15 Aug	15 Sep
Unfertilized					
cool season	429.6	834.9	1506.1	1232.0	1147.7
warm season	9.3	178.1	520.2	965.9	404.4
total native grass	438.9	1013.0	2026.3	2197.9	1552.1
introduced grass	0.0	0.0	0.0	0.0	0.0
forbs	31.4	199.5	231.6	222.6	203.4
total yield	470.3	1212.5	2257.9	2420.5	1755.5
Fertilized					
cool season	1085.4	2690.6	3260.0	2332.8	2233.6
warm season	54.2	71.0	229.8	162.7	126.1
total native grass	1139.6	2761.6	3489.8	2495.5	2359.7
introduced grass	0.0	201.2	895.9	707.1	264.0
forbs	10.7	205.5	480.3	638.0	133.2
total yield	1150.3	3168.3	4866.0	3840.6	2756.9

Table 8. Mean steer performance on native rangeland treatments, 1972-1976.

Treatments	Mean Steer Gain per Head (lbs)	Mean Steer Gain per Day (lbs)	Mean Steer Gain per Acre (lbs)
One grazing period 1972-1976			
Unfertilized	85.70a	1.40a	56.18a
Fertilized	90.50a	1.51a	89.10a

Means in the same column and followed by the same letter are not significantly different (P<0.05).

Table 9. Biweekly average daily gain for steers on native rangeland treatments, 1972-1976.

Treatments	1-15 Jun	16-30 Jun	1-15 Jul	16-31 Jul	1-15 Aug	16-31 Aug	1-15 Sep	Mean gain per Day
One grazing period 1972-1976								
Unfertilized		1.28	1.51	1.56	1.40	1.49	1.58	1.40
Fertilized		1.75	1.78	1.67	1.28	1.24	1.31	1.51

Table 10. Costs and returns after pasture costs for steers on native rangeland treatments, 1972-1976.

Treatments	Land Area per Period (acres)	Production Cost per Acre ($)	Cost per Period ($)	Steer Weight Gain per Period (lbs)	Steer Weight Value @ $0.70/lb ($)	Net Return per Steer ($)	Net Return per Acre ($)	Cost per Pound Steer Gain ($)
One grazing period 1972-1976								
Unfertilized	2.04a	8.76	17.87a	85.70a	59.99a	42.12a	20.80a	0.26a
Fertilized	1.38b	21.26	29.30b	90.50a	63.35a	34.05a	25.10a	0.40a

Means in the same column and followed by the same letter are not significantly different (P<0.05).

Table 11. Mean cow and calf performance on native rangeland treatments, 1978-1982.

	COW			CALF		
Treatments	Gain per Head (lbs)	Gain per Day (lbs)	Gain per Acre (lbs)	Gain per Head (lbs)	Gain per Day (lbs)	Gain per Acre (lbs)
One grazing period 1978-1979, 1981-1982						
Unfertilized	29.23a	0.74a	15.91a	83.98a	1.89a	44.93a
Fertilized	-1.65a	-0.03a	-1.50a	77.45a	1.51a	61.45a

Means in the same column and followed by the same letter are not significantly different (P<0.05).

Table 12. Biweekly average daily gain for cow-calf pairs on native rangeland treatments, 1978-1982.

Treatments	1-15 Jun	16-30 Jun	1-15 Jul	16-31 Jul	1-15 Aug	16-31 Aug	1-15 Sep	Mean gain per Day
One grazing period 1978-1979, 1981-1982								
Cow								
Unfertilized		1.23	1.23	0.22	0.25	-0.25		0.74
Fertilized		1.23	1.27	0.25	-0.88	-1.79	-2.52	-0.03
Calf								
Unfertilized		1.91	1.91	1.89	1.90	1.77		1.89
Fertilized		1.79	1.91	1.72	1.42	0.96	0.46	1.51

Table 13. Costs and returns after pasture costs for cow-calf pairs on native rangeland treatments, 1978-1982.

Treatments	Land Area per Period (acres)	Production Cost per Acre ($)	Cost per Period ($)	Calf Weight Gain per Period (lbs)	Calf Weight Value @ \$0.70/lb ($)	Net Return per Cow-Calf Pair ($)	Net Return per Acre ($)	Cost per Pound Calf Gain ($)
One grazing period 1978-1979, 1981-1982								
Unfertilized	1.83a	8.76	16.01a	83.98a	58.78a	42.77a	23.74a	0.21a
Fertilized	1.23b	21.26	26.15b	77.45a	54.22a	28.06a	23.21a	0.39a

Means in the same column and followed by the same letter are not significantly different ($P<0.05$).

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Alfalfa Interseeding has Major Problems and No Solutions

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Development of techniques to interseed alfalfa plants into intact native rangeland pastures was conducted for 21 years from 1969 to 1989 by grassland scientists at the North Dakota State University Dickinson Research Extension Center with four scientists contributing 37 scientist years to the subject for the purpose of providing greater herbage biomass and greater crude protein to grazing livestock in order to improve weight performance. This direction of research would only treat the symptoms without correcting the problem. Low herbage biomass production, deficient levels of crude protein after 1 August, and below genetic potential livestock weight gains were the symptoms of a deficiency in available mineral nitrogen in the soil of native rangelands caused by management with traditional grazing practices. Before it was known how to increase the quantity of soil available mineral nitrogen with a specific grazing management strategy, it was commonly presumed that interseeding alfalfa would be a suitable practice to compensate for the deficiency in crude protein and herbage biomass of the native forage plants.

Seedbed and Sod Control Required

N.E. Hansen, the famous alfalfa horticulturist of South Dakota Agricultural Experiment Station, promoted the use of *Medicago falcata* (pasture-type) alfalfa to increase production on the Northern Plains prairie by sending packets of seeds to homesteaders during the first two decades of the 1900's. Information with the seed packets claimed the seed would grow in cropland or broadcast into intact prairie (Rumbaugh c. 1979). There are a few known locations that alfalfa plants from Hansen's seed packets are still growing in native prairie. However, the rate of successful establishment of alfalfa plants by broadcast sod-seeding into native rangeland is phenomenally low. The seed must land on mineral soil and have extremely low competition for soil water, minerals, and sunlight.

Alfalfa seed requires access to mineral soil and reduced competition from the existing plant community. Mechanical preparation for a seedbed of mineral soil and effective sod control are essential. The problem is to find the appropriate size of mineral soil seedbed and type of sod control (table 1).

Early trials used 14-inch V-shaped lister blades for both seedbed preparation and sod control. The lister blade scalped a 14-inch wide seedbed and rolled out two 7-inch sod clods that were deposited upon the unplowed grassland on both sides of the furrow with a disturbed area of at least 28 inches wide creating an extremely rough landscape. On the remaining grassland, the herbage weight of short grasses decreased 60% and the herbage weight of mid grasses increased 31%. By the third year, the herbage weight of fringed sage and annual forbs greatly increased and smooth bromegrass had invaded all of the plowed areas as a result of the released nitrogen from the decaying organic matter in the overturned sod clods, the reduction in competition from short grasses, and the increase in available water (Goetz and Whitman 1978). The alfalfa plants had decreased to one plant per meter of row and almost all native plants had been lost by 35 years after the lister blade treatments. The invading smooth bromegrass was dominant and crested wheatgrass was subdominant (Manske 2004a).

Seedbeds prepared with 14 inch and 12 inch furrows were deemed to be too wide and highly susceptible to invasion by smooth bromegrass. The 1 inch seedbed produced less herbage from the interseeded species than the quantity of herbage lost by the treatment. The seedbeds with 2-, 3-, 4-, and 6-inch furrows and at 2-, 3-, 4-, 5-, 8-, and 10-foot row spacings were evaluated for 7 years (table 1).

The 2-inch furrow was unsatisfactory because much of the sod clods fell back into the furrow. The 3-inch twisted chisel plow shovel was the narrowest tool that produced an excellent seedbed with a "V" bottom and suitable width of the furrow. The 4- and 6- inch twisted chisels were wider but did not improve the density of established alfalfa plants (Manske 2004c).

The herbage production on the intact plant community on all row spacing treatments was greater than that produced on the control (table 2). The increase in herbage production on the intact portion of the treatment resulted from the increase in the amount of nitrogen released by the decaying organic matter in the overturned sod clod and the increase in availability of soil water from the removal of some plant competition during the mechanical sod treatment. However, the loss of herbage production from the disturbed seedbed areas was greater than the quantity of increase on the intact portion except for the treatment with 10-foot row spacings (table 2). Grass basal cover were lower on the 2-foot to 8-foot row spacing treatments than that on the control treatment. The grass basal cover was 3% greater on the 10-foot row spacing than that on the control. The 10-foot row spacing caused the fewest detrimental changes to the treated areas than any of the other row spacing treatments (Manske 2004b). Seedbed formation by mechanical treatment causes severe sod destruction.

Low Establishment Rate

Interseeding alfalfa into intact grassland ecosystems poses considerably greater problems than seeding alfalfa into cropland. Seeding alfalfa at the standard rate of 7 lbs PLS per acre (0.27 lbs PLS/row/acre) into cropland produces about 12 plants per meter of row (table 3). During interseeding trial I, the alfalfa varieties were seeded at 0.50 lbs PLS/row/acre (12.38 lbs PLS/acre) which was about double the cropland seeding rate, the plant density was less than 1 plant per meter of row (table 3). The desired minimum plant density was around 1 plant per foot or 3 plants per meter. Plant density on interseeding trial I fell way short of the desired density. During interseeding trial II, the alfalfa varieties were seeded at the same 0.50 lbs PLS/row/acre rate plus the competition from grass plants in the established community was reduced by undercutting with a 12-inch cultivator sweep, and the plant density was around 3.79 plants per meter of row which was an increase of 398% from interseeded trial I. However, the plant density on the interseeded trial II was 69% less than the plant density on cropland which was seeded with about one half the seeding rate. Seeding rate equivalents are shown in table 4.

Seeding rates on interseeded trials that were near the equivalent seeding rates on cropland yielded unsatisfactory plant densities. The seeding rate at about double the cropland seeding rates at 0.50 lbs PLS/row/acre yielded the best obtained seedling plant densities (table 4). Seeding rates at 1.00 lbs PLS/row/acre and greater did not yield increased plant densities greater than those on the 0.50 lbs PLS/row/acre treatments (Manske 2004d).

The differences in plant densities between interseeded trials I and II show the extent of competition from the grass plants on the established community. Grass plant composition suppressed alfalfa plant density 80% on interseeded trial I (table 3). Strongly indicating that mechanical sod control techniques are needed.

Sod control without removal of the sod requires the use of cultivator sweeps to control the established plant community adjacent to both sides of the seedbed furrow. The sweep fins can undercut the sod and separate the crowns of grass plants from a large portion of the grass plants' roots. The grass plants are not killed, but their growth processes are greatly impaired, and competition for soil water, and minerals are greatly reduced. The area undercut by 12-inch sweeps was adequate to reduce the competition sufficiently on both sides of the furrow. The area undercut by 6-inch sweeps was inadequate to reduce the competition enough. The 16-inch sweeps undercut a larger area, but the effects were not greater. The portion of the sweep directly over the furrow serves no function and on uneven terrain can cause disturbance to the seedbed. The tip of the cultivator sweep can be removed by cutting a reverse "V" with the widest part of the cut at the same width as the furrow (Manske 2004c).

Alfalfa plants form symbiotic relationships with rhizobium bacteria. These bacteria live in nodules on the roots and change (or fix) the nitrogen in soil air which is in a form that cannot be used by the alfalfa plants into a form of nitrogen that the alfalfa plant can use. The rhizobium bacteria must be mixed with the alfalfa seed. Option number one was to purchase the rhizobium bacteria in an inoculum and to mixed it with the alfalfa seed in a tub at planting time. Option number two was to ship the alfalfa seed to a company that applied the rhizobium inoculum in a protective coating unto the seed by an industrial process (Manske 2004d).

The level of nodulation on alfalfa plant roots affects the potential amount of nitrogen fixation and the quantity of plant production. Evaluation of the amount of nodule formation on excavated alfalfa seedling roots with inoculation by tub mixed and seed coated methods was conducted.

All of the excavated plant roots from both inoculation methods had fewer than three small nodules and most plants had no nodules. There was no difference between the inoculation methods (Manske 2004d).

Low nodulation rates on interseeded alfalfa plant roots from both inoculation methods indicates that the rhizobium bacteria did not survive in the grassland soil long enough to permit infection into young alfalfa plant root material. Grassland soils have populations of bacteria, protozoa, and nematodes that are capable of rapidly consuming the rhizobium bacteria (Manske 2004d). The low nodulation rates of interseeded alfalfa plants explains why alfalfa plants interseeded into grasslands develop at very slow rates and have high mortality rates causing low established rates.

Alfalfa Becomes Competition for Grasses

Established alfalfa plants become major competition to grasses for sunlight, soil mineral nitrogen, and soil water. Mature alfalfa plants are taller than most grass leaves. The shadow of the alfalfa plants reduce the quantity of sunlight reaching the grass leaves below native grass light saturation points (Peltzer and Kochy 2001). Native grasses have high light saturation points and require near full sunlight. Warm season grasses have higher light saturation points than cool season grasses (Kochy 1999, Kochy and Wilson 2000). Shading reduces native warm season grasses more than native cool season grasses. Introduced cool season domesticated grasses have lower light saturation points than native grasses, permitting domesticated grasses to live in low light conditions.

Low amounts of sunlight reaching native grass leaves decrease the rate of photosynthesis, which reduces the quantity of atmospheric carbon dioxide fixed, reducing the quantity of simple carbohydrates produced (Coyne et al. 1995). Low quantities of carbohydrates cause decreases in growth of roots, leaves, and stems, and development of secondary tillers. Low quantities of carbohydrates also cause increases in the rates of leaf senescence and increases in tiller mortality that results in reductions of native grass plant density (basal cover) and reductions of herbage biomass production (Langer 1972, Grant et al. 1983, Briske and Richards 1995). The competition for sunlight results in losses of native plants.

Mature alfalfa plants use a high portion of the low available soil mineral nitrogen. The interseeded alfalfa seeds were inoculated with rhizobium bacteria which had been consumed by the indigenous soil organisms resulting in extremely low levels of bacteria infection and nodulation with almost no nitrogen fixation (Manske 2004d). The nitrogen that mature alfalfa plants needed to use had to be withdrawn from the soil. Grass plants also needed to absorb mineral nitrogen from the soil and build essential nitrogen compounds of amino acids and nucleotides. Amino acids are building blocks of proteins that form enzymes, hormones, and important structural components of cells. Nucleotides, deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), are the genetic material that control all cellular functions and heredity (Manske 2009). Low quantities of available soil mineral nitrogen is the major limiting factor of herbage growth on rangelands (Wight and Black 1979). Low available soil mineral nitrogen results in greatly reduced density of native grass species.

Mature alfalfa plants have a high water use. Soil water depletion by alfalfa plants was evaluated from the crown along perpendicular transects with five holes to a four foot depth placed at one foot intervals collected during mid July on 3 replication over 3 years and compared to native rangeland without alfalfa (Manske 2004b).

The alfalfa plants depleted soil water from 5 holes to a four foot depth an average of 35% greater on 3 replications over a 3 year period than that on soil with native rangeland plants and no alfalfa (table 5). The high depletion of soil water by interseeded alfalfa plants causes severe water stress in the adjacent plant community which results in a shift from native species to domesticated species of smooth bromegrass and crested wheatgrass.

Established interseeded alfalfa plants are a serious source of competition for sunlight, soil mineral nitrogen, and soil water for the adjacent native plants.

Livestock Performance Not Improved

Alfalfa interseeding into native rangeland was intended to increase the herbage biomass and crude protein of available forage that should improve cow and calf weight performance. Unfortunately, the cow and calf weight gain per head and gain per day were not improved (Manske 2004e).

Cow-calf weight performance on a 10 acre alfalfa interseeded pasture and on an 18 acre native rangeland pasture was evaluated in two grazing trials. Trial I had one grazing period during July with the native rangeland stocked at 2.21 ac/AUEM and the alfalfa interseeded stocked at 1.36 ac/AUEM (table 6). Trial II had two grazing periods with the first during June and the second during late July to late August with the native rangeland stocked at 1.85

ac/AUEM and the alfalfa interseeded stocked at 1.01 ac/AUEM (table 6).

Cow and calf weight performance during trial I on the native rangeland and alfalfa interseeded pastures managed with one grazing period were not significantly different (table 7). The weight performance was larger on the native rangeland pasture. Cow gain per head was 84.1% larger. Cow gain per day was 278.9% larger. Cow gain per acre was 21.9% larger (table 7). Calf gain per head was 8.7% larger. Calf gain per day was 6.6% larger. However, calf gain per acre on the alfalfa interseeded was 40.4% larger (table 7).

Cow and calf weight performance during trial II on the native rangeland and alfalfa interseeded pastures managed with two grazing periods were not significantly different except the calf gain per acre was significantly greater on the alfalfa interseeded pasture (table 8). The weight performance was larger on the alfalfa interseeded pasture. Cow gain per head was 13.6% larger. Cow gain per day was 16.8% larger. Cow gain per acre was 104.5% larger (table 8). Calf gain per head was 11.7% larger. Calf gain per day was 10.4% larger. Calf gain per acre was 101.1% significantly greater (table 8).

Aboveground herbage biomass during trial I on the native rangeland and alfalfa interseeded pastures managed with one grazing period was not significantly different. The herbage biomass at the end of the grazing period on the alfalfa interseeded pasture was 47.2% grass and 52.8% alfalfa and the total was 29.5% larger than the total remaining on the native rangeland pasture but not significantly different (table 9).

Aboveground herbage biomass during trial II on the native rangeland and alfalfa interseeded pastures managed with two grazing periods was not significantly different. The herbage biomass at the end of the second grazing period on the alfalfa interseeded pasture was 49.0% grass and 51.0% alfalfa and the total was 73.2% larger than the total remaining on the native pasture but not significantly different (table 10).

The total basal cover and basal cover for cool season grasses, warm season grasses, sedges, and forbs were lower on the alfalfa interseeded pasture but not significantly different from those on the native rangeland pasture. The basal cover for invader grass species on the alfalfa interseeded pasture was 1333.3% greater and significantly different than that on the native rangeland pasture. The basal cover for alfalfa was 3.16% and was 100% greater on the alfalfa interseeded pasture that was significantly greater because the native rangeland had no alfalfa.

Cow-calf pairs during trial I on the alfalfa interseeded pasture used 46.7% less land area and had 21.2% lower pasture costs but not significantly. Calves on the alfalfa interseeded pasture gained 8.7% lower weight but not significantly. Because of lower land use and lower pasture costs, the calves on the alfalfa interseeded pasture had 2.2% greater net return per head but not significantly and 91.8% greater net return per acre but not significantly and had 15.2% lower cost per pound of calf gain but not significantly (table 11).

Cow-calf pairs during trial II on the alfalfa interseeded pasture used 45.1% less land area and had 18.9% lower pasture costs that was significant. Calves on the alfalfa interseeded pasture gained 11.7% greater weight but not significantly. Because of lower land use and lower pasture costs, the calves on the alfalfa pasture had 26.8% greater net return per head but not significantly and 131.0% greater net return per acre that was significant and had 26.1% lower cost per pound of calf gain that was significant (table 12).

The returns per acre were greater on the alfalfa interseeded pasture during trial II , however, not during trail I, but the returns per cow-calf pairs on both trial I and trial II were not different on the alfalfa interseeded and native rangeland pastures (Manske 2004e).

Summary

Alfalfa seed needs mineral soil and seedlings require reduced competition for sunlight, soil mineral nitrogen, and soil water from the intact grassland plants. Mechanical formation of mineral seedbeds causes severe sod destruction and decreased native grass herbage biomass production.

Interseeding furrow seeding rate at 0.50 lbs PLS/row/acre that is double the standard cropland seeding rate yields 69% lower plant density. If the seedbed formation treatment does not include the additional sod control treatment with cultivator sweeps that undercut adjacent grass plants, the resulting alfalfa plant densities will be reduced by 80%. Alfalfa require symbiotic rhizobium bacteria in order to fix soil air nitrogen, but are not able to function together when inoculated into grassland soils because the indigenous soil organisms consume the rhizobium before seedling roots develop. These conditions result in very slow growth rates and high mortality rates causing low establishment rates.

Mature alfalfa plants cause serious competition to intact native grass plants by reducing access to sunlight, soil mineral nitrogen, and soil water resulting in reduced native grasses and huge increases of domesticated species of smooth bromegrass and crested wheatgrass.

The total aboveground herbage on alfalfa interseeded pastures is larger than that on native rangeland pastures but not significantly. The interseeded pasture herbage includes a high amount of fringed sage and other weeds and increasing invaded grasses that mature early. Cow and calf pairs grazing alfalfa interseeded pasture do not gain weight per head and per day at rates greater than the cows and calves grazing native rangeland.

Interseeding alfalfa into intact native rangeland causes severe additional major problems and does not solve the intended previously existing problems.

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Table 1. Land area of seedbed prepared by interseeding machine in square feet and percentage of an acre and the sod clod pulled out of the furrow would disturb an additional area of about equal size on the intact grassland.

Row Spacing		2 inch furrow	3 inch furrow	4 inch furrow	6 inch furrow	12 inch furrow	14 inch furrow	# Rows per rod
2 foot	sq ft	3703	5445	7187	10890	21780	25410	8.25
	%	8.50	12.50	16.50	25.00	50.00	58.33	
3 foot	sq ft	2468	3630	4792	7260	14520	16940	5.50
	%	5.67	8.34	11.00	16.67	33.34	38.89	
4 foot	sq ft	1854	2726	3598	5452	10904	12721	4.13
	%	4.26	6.25	8.26	12.52	25.00	29.20	
5 foot	sq ft	1481	2178	2875	4356	8712	10164	3.30
	%	3.40	5.00	6.60	10.00	20.00	23.30	
8 foot	sq ft	925	1362	1795	2723	5446	6354	2.06
	%	2.12	3.13	4.12	6.25	12.50	14.59	
10 foot	sq ft	741	1089	1437	2178	4356	5082	1.65
	%	1.70	2.50	3.30	5.00	10.00	11.67	

Table 2. Total herbage biomass determined for only the intact portion and for the combined intact and disturbed portions of each treatment.

	Total herbage biomass on only the intact portion of each treatment		Total herbage biomass on the combined intact and disturbed areas of each treatment	
Row Spacing	lbs/ac	% of control	lbs/ac	% of control
Control	1198.80	100.00	1198.80	100.00
2 foot	1416.30	118.14	920.17	76.76
3 foot	1501.92	125.29	1127.49	94.05
4 foot	1431.46	119.41	1203.71	100.41
5 foot	1315.30	109.72	1091.57	91.06
8 foot	1329.76	110.92	1194.66	99.65
10 foot	1370.26	114.30	1217.20	101.53

Table 3. Alfalfa plant density per meter of row, seeding rate on interseeded trials double the rate on cropland trial, mean of 3 reps, years 2, 3, and 4.

Alfalfa Variety	Cropland	Interseeded Trial I	Interseeded Trial II
Anik	12.86	0.40	3.21
Drylander	11.09	0.50	2.99
Kane	11.74	0.55	4.69
Rangelander	12.17	0.87	3.66
Spredor II	12.10	0.80	3.97
Travois	12.33	1.41	4.24

Table 4. Determination of seeding rates for interseeded and solid seeded treatments from seven interseeded furrow seeding rates.

Interseeding Furrow seed rate lbs LS/row/acre	Equivalent Solid seed rate lbs PLS/acre	Interseeding Treatment seed rate lbs PLS/acre								
		Row Spacing								
		1 ft	2 ft	3 ft	4 ft	5 ft	6 ft	8 ft	10 ft	25 ft
0.25	6.19	4.13	2.06	1.38	1.03	0.83	0.69	0.52	0.41	0.17
0.50	12.38	8.25	4.13	2.75	2.07	1.65	1.38	1.03	0.82	0.33
0.60	14.85	9.90	4.95	3.30	2.48	1.98	1.65	1.24	0.99	0.40
0.75	18.56	12.38	6.19	4.13	3.10	2.48	2.06	1.55	1.24	0.50
1.00	24.75	16.50	8.25	5.50	4.13	3.30	2.75	2.06	1.65	0.66
1.50	37.13	24.75	12.38	8.25	6.20	4.95	4.13	3.09	2.48	0.99
2.00	49.50	33.00	16.50	11.00	8.26	6.60	5.50	4.12	3.30	1.32

Table 5. Mean inches of soil water during mid July at one foot intervals from crown of interseeded alfalfa plant compared to native rangeland without alfalfa, 3 reps, 3 years.

	Distance from interseeded alfalfa plant (feet)					
Soil Depth (inches)	1	2	3	4	5	Native Range Control
0-6	0.83	0.82	0.84	0.83	0.87	0.87
6-12	0.62	0.62	0.58	0.58	0.62	0.69
12-24	0.85	0.82	0.80	0.92	0.89	1.87
24-36	0.96	0.78	0.81	0.84	0.86	1.86
36-48	0.68	0.88	0.74	0.90	0.85	0.77
0-48	3.94	3.92	3.77	4.07	4.09	6.06
% Depletion	-35.0	-35.3	-37.8	-32.8	-32.5	

Table 6. Mean stocking rates on treatments managed with one grazing period and with two grazing periods.

						Stocking Rate	
Treatments	Dates Pasture Grazed	Days in Period	Months in Period	No. of cow-calf pairs	No. of AUEM	AUEM per acre	Acres per AUEM
One grazing period 1979-1981, 1984							
Native Range	3 Jul-1 Aug	29	0.95	8	8.13a	0.45a	2.21a
Alfalfa Interseeded	3 Jul-28 Jul	25	0.82	8	7.36a	0.74a	1.36a
Two grazing periods 1985-1988							
Native Range	9 Jun-24 Jun	15	1.44	6	9.78x	0.55x	1.85x
	22 Jul-20 Aug	29					
Alfalfa Interseeded	9 Jun-24 Jun	15	1.44	6	9.92x	0.99y	1.01y
	22 Jul-20 Aug	29					

Means in the same column and followed by the same letter are not significantly different (P<0.05).

Table 7. Mean cow and calf performance on treatments managed with one grazing period.

	COW			CALF		
Treatments	Gain per Head (lbs)	Gain per Day (lbs)	Gain per Acre (lbs)	Gain per Head (lbs)	Gain per Day (lbs)	Gain per Acre (lbs)
One grazing period 1979-1981, 1984						
Native Range	15.31a	0.52a	7.99a	56.13a	1.97a	26.09a
Alfalfa Interseeded	2.43a	-0.93a	6.24a	51.23a	1.84a	43.77a

Means in the same column and followed by the same letter are not significantly different ($P<0.05$).

Table 8. Mean cow and calf performance on treatments managed with two grazing periods.

	COW			CALF		
Treatments	Gain per Head (lbs)	Gain per Day (lbs)	Gain per Acre (lbs)	Gain per Head (lbs)	Gain per Day (lbs)	Gain per Acre (lbs)
Two grazing periods 1985-1988						
Native Range	47.30x	1.13x	15.77x	99.80x	2.30x	33.27x
Alfalfa Interseeded	53.75x	1.32x	32.25x	111.48x	2.54x	66.89y

Means in the same column and followed by the same letter are not significantly different ($P<0.05$).

Table 9. Mean aboveground herbage biomass and forage utilized on treatments managed with one grazing period.

	Aboveground Herbage Biomass			
	Period #1		Forage Utilized	Forage per cow-calf pair
Treatments	ungrazed (lbs/acre)	grazed (lbs/acre)	(lbs/acre)	(lbs/day)
One grazing period 1979-1981, 1984				
Native Range	1410.83a	832.50a	578.33a	44.87
Alfalfa Interseeded	1925.14a	1077.84a	847.30a	42.37

Means in the same column and followed by the same letter are not significantly different (P<0.05).

Table 10. Mean aboveground herbage biomass and forage utilized on treatments managed with two grazing periods.

	Aboveground Herbage Biomass					
	Period #1		Period #2		Forage Utilized	Forage per cow-calf pair
Treatments	ungrazed (lbs/acre)	grazed (lbs/acre)	ungrazed (lbs/acre)	grazed (lbs/acre)	(lbs/acre)	(lbs/day)
Two grazing periods 1985-1988						
Native Range	1688.77x	948.57x	1357.87x	841.75x	1256.32x	85.66
Alfalfa Interseeded	2567.66x	1911.97x	2595.62x	1457.70x	1793.61x	67.94

Means in the same column and followed by the same letter are not significantly different (P<0.05).

Table 11. Costs-returns on treatments managed with one grazing period.

Treatments	Acres per Period (Acres)	Cost per Acre ($)	Cost per Period ($)	Calf Gain per Period (lbs)	Calf Value @ $0.70/lb ($)	Net Return per Cow-Calf pair ($)	Net Return per Acre ($)	Cost per pound Accumulated Weight ($)
One grazing period 1979-1981, 1984								
Native Range	2.10a	8.76	18.39a	56.13	39.29a	20.90a	9.95a	0.33a
Alfalfa Interseeded	1.12b	12.94	14.49a	51.23	35.86a	21.37a	19.08a	0.28a

Means in the same column and followed by the same letter are not significantly different (P<0.05).

Table 12. Costs-returns on treatments managed with two grazing periods.

Treatments	Acres per Period (Acres)	Cost per Acre ($)	Cost per Period ($)	Calf Gain per Period (lbs)	Calf Value @ $0.70/lb ($)	Net Return per Cow-Calf pair ($)	Net Return per Acre ($)	Cost per pound Accumulated Weight ($)
Two grazing periods 1985-1988								
Native Range	2.64x	8.76	23.13x	99.80	69.86x	46.73x	17.70x	0.23x
Alfalfa Interseeded	1.45y	12.94	18.76y	111.48	78.03x	59.27x	40.88y	0.17y

Means in the same column and followed by the same letter are not significantly different (P<0.05).

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Can Prescribed Fire Impact Grassland Ecosystem Processes

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Can prescribed fire on grasslands of the Northern Plains impact more than the aboveground vegetation. The impacts of prescribed fire on encroached woody species and on degraded grassland ecosystems were evaluated for the above and below ground components.

Fire has been a recurrent environmental factor on grasslands from their beginning, as has drought. The presence of fire does not prove that grasslands need or are caused by fire (Heady 1975).

Albeit, many grassland ecologists have observed that the occurrence of fire was the force that prevented intrusion of shrubs and trees into grasslands (Weaver 1954, Humphrey 1962, Daubenmire 1974, Stoddart, Smith, and Box 1975, Wright and Bailey 1982), and, the obvious corollary, that suppression of fire has facilitated the invasion of woody shrubs and trees into grasslands (Humphrey 1962, Stoddart, Smith, and Box 1975, Wright and Bailey 1982). This observational concept is almost universally accepted among modern grassland ecologists. Nevertheless, the processes of how fire can restore degraded grassland ecosystems and reverse or prevent woody species encroachment into prairie have not been clearly explained.

Fire damages, kills, or consumes the aboveground parts of grasses, forbs, shrubs, and trees. The severity of the effects of fire on plant species varies with the amount of soil water, the quantity of fine fuel, and the seasonal period and frequency of the burns.

Bailey and Anderson (1980) determined the range in temperatures reached during prescribed burning by using commercial temperature pellets that melt at specific temperatures placed on asbestos cards attached at different heights to metal posts located within grassland and shrubland communities (table 1). Grasslands burned at comparatively low temperatures ranging from 199.4 to 800.6 F (93 - 427 C). Temperature at the soil surface was 278.6 F (137 C) for grassland backfires and 402.8 F (206 C) for grassland headfires (table 1). Shrublands burned at higher temperatures ranging from 399.2 to 1299.2 F (204 -704 C). Temperature at the soil surface was 617 F (325 C) for shrubland backfires and 815 F (435 C) for shrubland headfires (table 1). All of the temperatures measured at or above the soil surface were greater than the lethal temperature for leaf tissue, which is approximately 140 F (60 C), the temperature that crude protein is denatured.

The historical fire return interval has been estimated to have been 3 to 4 years for tall grass prairie, 5 to 10 years for moist mixed grass prairie, and around 25 years for dry mixed grass prairie, including the northern short grass prairie (Wright and Bailey 1982, Bragg 1995). The seasonal period when fires occurred was interpreted from a review of extensive historical grassland fire information by Higgins (1986). Lightning-set fires occurred during summer and early fall, with 73% occurring during July and August. The Indian-set fires occurred primarily during two periods, March through May with a peak in April, and July through early November with a peak in October (Higgins 1986).

Can Fire Reverse Encroachment of Woody Species into Grasslands

Encroachment of woody species into grasslands has been a great problem since the early homestead period. The presumed primary cause for woody plant invasion into grasslands is the suppression of fire but the related processes have not been explained. In order for fire to prevent encroachment of woody plants into grasslands, fire would need to prevent woody plant seed production, seedling establishment, and be able to totally destroy established woody plants.

Preventing seed production would require short fire return intervals and complete burns to stop trees and shrubs from maturing to seed producing age. Long fire return intervals and partial or incomplete burns would permit trees and shrubs time to develop long enough to mature and produce seeds. Seed dispersal is by wind, birds, squirrels, and other mammals. Most woody species produce seeds that have low germination rates, seedlings that have low competitiveness with grass sod, and seedlings that mostly have low establishment rates. Establishment of woody plant seedlings into grassland ecosystems generally requires some type of preceding activity that disrupts the continuity of the grassland structure providing open bare moist soil spots. Grassland fires tend to increase the number and size of open soil spots for a couple of growing seasons. Without coincidental damage to grassland structure, woody plant seedlings would not be able to become established in grasslands.

Removal of established woody species from grasslands with fire was evaluated for fifty three of the major woody species that have encroached into grasslands of the Northern Plains. The woody species were evaluated by type of regeneration, effects from fire, and location of vegetative buds.

All of the invasive woody species, 53 (100%), regenerate by sexual reproduction and produce seeds (table 2). Fifty (94.3%) of the woody species have some type of reproduction by vegetative growth. Fire can cause total plant kill in only five (9.4%) of the woody species, common juniper, creeping juniper, Rocky Mountain juniper, ponderosa pine, and big sagebrush (table 2). These five woody species do not have vegetative buds (table 3). The three junipers are usually totally consumed by fire because they contain flammable resins. Mature ponderosa pine have thick trunk bark that insulates the cambium tissue from heat damage from light to moderate ground fires. Fire can kill total plants of young ponderosa pine that do not have thick bark and can kill total plants of mature pine when fire reaches the crown. Big sagebrush is not fire resistant and is the only deciduous plant in the Northern Plains that can be totally killed by fire.

The vast majority, 48 (90.6%), of the invasive woody species are not totally killed by fire, however, these plants do receive enough injury from fire that results in top kill of the aboveground stems and foliage (table 2). The partial damage or top kill caused by fire activates sprout growth from vegetative buds located on surviving plant parts of these 48 (90.6%) invasive woody species (table 2). Vegetative buds can be located on the root crowns, stem bases, rhizomes, stolons, lateral roots, or on the trunk of woody species (table 3). Woody species can have vegetative buds located at one to four different locations (table 3). Vegetative buds are hormonally controlled from active growth by apical dominance of the stems. When fire consumes or damages aerial stems, the growth inhibiting hormone control is removed releasing some to several vegetative buds for each stem to development into vegetative sucker shoots.

In addition, thirteen (24.5%) of the woody species have the ability to develop adventitious roots on aerial stems that have by some mechanism been bent down with parts of the stem touching soil (table 3).

Anderson and Bailey (1980) evaluated the effects from annual early spring burning during April for 24 years of shrub encroached grassland and analyzed frequency, canopy cover, and woody stem density data collected on both burned and unburned treatments (table 4). Annual burning for 24 years resulted in increased frequency and canopy cover of grasses, sedges, and perennial forbs. Competition for sunlight was temporarily reduced after each annual fire consumed the replacement aerial stems of shrubs. Fringed sage increased in frequency (133.3%) and in canopy cover (50.0%) on the burned treatments. The early spring fires were deleterious to cool season grasses. The annually burned areas had lower soil water than the unburned areas. This condition resulted from reduced infiltration rates and greater evaporation loss. Water stress in grasses and sedges on the burned areas caused a reduction of leaf blade length (43.8%) and herbage biomass production (48.9%). Annual burning prevented litter accumulation; the greater area of exposed soil surface in burned areas resulted in a more favorable seedbed. Organic matter was greater in the top 6 inches (15 cm) of soil on the burned areas than on the unburned areas. Total mineral nitrogen (NH_4 & NO_3) and other nutrients were not different on the burned and unburned areas. Annual burning increased shrub frequency (64.7%) and reduced shrub canopy cover (56.3%), shrub height, and shrub herbage biomass (94.6%). Because of the vast quantity of vegetative suckers produced by shrubs after fire, annual early spring burning did not eliminate any woody species from the plant community. Stem density of shrubs was 245.5% greater on the burned areas than on the unburned areas (table 4).

Evaluation of 53 of the major woody species that encroach grasslands of the Northern Plains found that, only 5 (9.4%) of these invasive woody species can be totally killed and removed from the ecosystem with fire. These 2 conifer trees, 2 conifer shrubs, and 1 deciduous shrub do not reproduce by vegetative buds. The other 48 (90.6%) deciduous woody species can reproduce by vegetative buds from which vegetative secondary suckers can grow and produce replacement aerial stems. Fire can severely damage or top kill the aerial stems of these invader woody species but can not remove any of these species from the grassland ecosystem. Annual fires for 24 years can not remove deciduous woody species that reproduce by vegetative buds from the grassland ecosystem that they have encroached.

It strongly appears that the historical concept that fire can prevent woody species encroachment into grassland ecosystems was based on short term observations that misinterpreted top kill of woody species as total plant kill.

Can Fire Restore Degraded Grasslands

Manske (2007) evaluated effects of repeated burning on degraded Northern Plains mixed grass prairie having one, two, three, and four burns repeated on a mean return interval of 3.65 years over a treatment period of 13 years. Insufficient production of plant biomass for fuel prevented annually repeated burns. The burn regime was designed to reduce the encroaching western snowberry and the increasing introduced cool season grasses. The changes in vegetation were evaluated by aboveground herbage biomass and plant shoot cover (% shoot frequency). The ecosystem functions were evaluated by endomycorrhizal fungal infection rates, soil microorganism activity by quantity of available inorganic (mineral) nitrogen and gravimetric soil water.

The total current year's aboveground biomass was low and not significantly different after one, two, three, and four burns compared to the biomass produced on the unburn treatment (table 5). However, the composition of the aboveground biomass changed remarkably. The contribution of grasses changed from 24.2% on the no burns to 65.6% after four burns, an increase of 171.1%. The contribution of sedges changed little from 13.2% on no burns to 11.1% after four burns. The contribution of forbs after one burn was 139.7% greater than that on the no burns, then vastly decreased and was 35.3% greater after four burns than that on the no burns. The biomass contribution from shrubs changed from 47.5% on no burns to only 3.0% after four burns.

Grass biomass decreased 24.7% after one burn and increased 109.3% after four burns. Sedge biomass increased 61.6% after one burn and decreased 35.1% after four burns. Forb biomass increased 78.0% after one burn and increased 4.4% after four burns. Shrub biomass decreased 83.1% after one burn and decreased 95.1% after four burns (table 5).

Shoot frequency of native grasses was thin but widely distributed and increased 94.7% after four burns. Native grass shoot frequency increased significantly after three and four repeated burns (table 6). However, the quantity of basal cover area for native grasses was scant and not well developed after four burns.

Shoot frequency of sedges increased 71.1% after two burns then decreased and was not significantly different after three and four burns (table 6).

Introduced grass shoot frequency decreased 65.1% after four burns (table 6). Kentucky bluegrass shoot frequency decreased 36.2% after four burns. Quackgrass shoot frequency decreased an average of 90.9% after three and four burns. Smooth bromegrass shoot frequency decreased an average 96.7% after three and four burns. Four burns were required to reduce introduced cool season grasses significantly.

Perennial forb shoot frequency increased 39.3% after one burn then decreased to 4.3% greater and were not significantly different after four burns. Early succession and weedy forb shoot frequency increased 8.2% after one burn then decreased 50.9% after four burns. Four burns were required to reduce weedy forbs significantly (table 6).

Shrub shoot frequency decreased 36.4% after one burn and continued to decrease 58.2% after four burns. Four burns were required to reduce shrubs significantly (table 6).

Western snowberry shoot frequency decreased 62.7% after one burn and decreased 64.0% after four burns. Shoot frequency of western snowberry changed little from repeated burns after the first burn because of the increased sucker shoot growth after each fire. The aboveground biomass produced was greatly reduced after three and four burns.

All burns cause some damage to plants, but the seasonal period that prescribed burns are conducted affects the shoot frequency of plants differently. Western wheatgrass increased after mid-late April burns and decreased after May-mid June burns. Blue grama shoot frequency decreased after mid-late April burns and increased after May-mid June burns. Kentucky bluegrass shoot frequency increased after mid-late April burns and decreased after May-mid June burns. Smooth bromegrass shoot frequency had the greatest decrease after mid-late April burns and mid June-July burns. Quackgrass shoot frequency had the greatest decrease after May-mid June burns and mid June-July burns (table 7).

Sedge shoot frequency decreased after mid-late April burns and increased after May-mid June burns (table 7).

Perennial forb shoot frequency increased after mid-late April and mid June-July burns and decreased after May-mid June burns. Weedy forb shoot frequency increased after mid-late April burns and decreased after May-mid August burns (table 8).

Silverberry shoot frequency had the greatest decrease after mid-late April burns and early-mid August burns. Western rose shoot frequency had the greatest decrease after mid-late April burns and May-mid June burns. Western snowberrry shoot frequency had the greatest decrease after mid-late April burns and May-mid June burns (table 8).

The endomycorrihizal fungal infection rate on native grass roots was low at a mean of 72.9% and was not significantly different among no burns and burn treatments. Prescribed repeat burning does not increase endomycorrhizal fungal infection on native grass roots (Manske 2007).

The quantity of soil water during the growing season to 24 inches (60.9 cm) in depth was low at a mean of 1.45 inches/foot and was not significantly different among no burns and burn treatments. Prescribed repeat burning does not activate the endomycorrhizal fungi to form water stable soil aggregates that would increase water infiltration (Manske 2007).

The quantity of available mineral nitrogen (NH_4 & NO_3) was extremely low at a mean of 27.8 lbs/ac and was not significantly different among no burns and burn treatments. Prescribed repeat burning does not increase the quantity of soil organic nitrogen to be mineralized into inorganic nitrogen by the endomycorrhizal fungi and other soil microbes. The extremely low available mineral nitrogen was the reason the annual herbage biomass production remained low (Manske 2007).

The grass plant growth mechanisms of nutrient resource uptake, water use efficiency, vegetative reproduction by tillering, and compensatory physiological mechanisms were nonfunctional or extremely low because the quantity of available mineral nitrogen was well below the minimum required quantity of 100 lbs/ac. The ecosystem biogeochemical processes performed by the soil rhizosphere microbes did not occur because the biomass of the soil microbes was too small. Prescribed repeat burning does not and cannot activate any of the necessary grass plant growth mechanisms and ecosystem biogeochemical processes. These mechanisms and processes must be biologically functional in order to restore degraded grassland ecosystems (Manske 2018).

Four repeated prescribed burns can modify the composition of the aboveground vegetation in degraded grassland ecosystems. The composition of introduced cool season grasses, early succession and weedy forbs, and the aerial stems of invasive shrubs can be temporarily decreased while the burn regime continues (Manske 2007). The degraded grassland ecosystem remains deteriorated. The problem with undesired plants returns to the persistently degraded ecosystem when the burning regime terminates.

Fire does not improve grassland ecosystems biologically or ecologically. Fire and drought are recurring environmental factors that grassland ecosystems must endure. Fire cannot replace the necessary beneficial effects of partial defoliation from grazing graminivores (Manske 2018).

Woody Encroachment Only After Degradation

Traditional management practices focus only on the aboveground components from the perspective of the "use" failing to consider grasslands as complex ecosystems and neglecting to address the biological needs of all above and belowground ecosystem components. The periods of defoliation by grazing are not coordinated with grass phenological growth stages resulting in decreases in the quantities of carbon exudates released through the grass roots into the rhizosphere, reducing the rhizosphere volume, decreasing the organism biomass and activity, and reducing the rates and quantities of soil organic nitrogen mineralized into inorganic nitrogen. These typical deficient quantities of available mineral nitrogen cause the physiological grass growth mechanisms to function at greatly reduced levels resulting in incomplete recovery of grazed grass tillers replacing less leaf and stem material than the quantity removed by grazing. These conditions cause a huge decrease in tiller density and herbage production and also result in a steady decline in the ecosystem biogeochemical processes and a reduction in the grass growth mechanisms of nutrient resource uptake competitiveness. This degradation of grassland plant communities, grass growth mechanisms, and ecosystem biogeochemical processes creates numerous large bare spaces that have only diminished competition from the depaupered native grass plants forming suitable habitat for opportunistic invading grasses and forbs and encroaching shrubs and trees to become established in degraded grassland ecosystems (Manske 2013).

The existence of a woody component in a grassland plant community is not an ecological beneficial relationship. Woody species and grasses are adversarial inhibitive competitors. Grasses and woody species compete for sunlight, mineral nitrogen, and soil water.

The degree of difference in competitive abilities between prairie grasses and shrubs on the mixed grass prairie was investigated during 1994 to 1998 at the University of Regina, Saskatchewan, with direction from Dr. S.D. Wilson. The grass growth form has competitive advantages over the shrub growth form. The per gram of biomass effects on resource use efficiency are smaller for shrub growth forms than grass growth forms (Kochy and Wilson 2000). Shrubs must use a portion of the photosynthates produced in the leaves to build and maintain their unproductive woody stems; the result is a great reduction in resource uptake efficiency. Shrubs require 6 times greater aboveground biomass than the grasses before grass production is decreased as a result of competition from the shrubs (Kochy 1999). Grass aboveground biomass is primarily productive photosynthetic leaves; the result is a high resource uptake efficiency. Grasses have a 1.4 times greater per gram of biomass resource efficiency effect than shrubs (Kochy 1999). Grasses on prairie habitat attenuated more light, took up more mineral nitrogen, and took up more soil water per gram of biomass than did shrubs on brush habitat (Kocky 1999, Kochy and Wilson 2000). Because grasses have high root: shoot ratios and no woody stems to maintain; grasses are good competitors for belowground resources and superior competitors for mineral nitrogen. Shrub's taller growth form makes the plants superior competitors for aboveground resources (Kochy and Wilson 2000).

Competition between shrubs and grasses during early stages of shrub expansion into prairie habitat with healthy grasses is primarily for belowground resources of nutrients and soil water; under these initial conditions, grasses have the advantage and the shrubs are suppressed (Kochy and Wilson 2000, Peltzer and Kochy 2001). Competition from healthy grasses also reduces the growth rates of shrub rhizomes and causes high mortality rates of young suckers, preventing expansion into healthy grass communities (Li and Wilson 1998). Seedlings of grasses, forbs, and shrubs are also unable to compete effectively for resources in healthy established grass plant communities and are suppressed (Peltzer and Kochy 2001). Successful competition of grasses for belowground resources prevents shrubs from becoming established in healthy grass communities.

Shrubs can compete for some of the belowground resources only after the grass plants have been degraded by antagonistic management practices. Following the reduction in the grass plant growth mechanisms of nutrient resource uptake competitiveness, establishment of shrubs can occur in degraded grasslands, which frequently start as clumps (Li and Wilson 1998). The belowground resources previously used by the healthy robust grasses, but no longer consumed by the smaller, less vigorous degraded grasses, are taken up by the shrub plants resulting in proportional increases of biomass production (Kochy and Wilson 2000). After grass competition for belowground resources is reduced, shrub rhizome suckers can regain the faster growth rates and higher survival rates (Li and Wilson 1998) resulting in greater shrub stem densities. As shrub stem density increases, the competition shifts to primarily the aboveground resources of light; under these different degraded conditions, shrubs have the advantage and the grasses are strongly suppressed (Kochy and Wilson 2000).

The reduction of the competitiveness of the grasses for belowground resources of mineral nitrogen and soil water in conjunction with diminution of the physiological grass growth mechanisms and degradation of the ecosystem biogeochemical processes in the grass plant communities that resulted from antagonistic management practices fully explains the encroachment of woody shrubs and trees growing in degraded grassland ecosystems.

Encroachment of woody plants into grassland communities has not been the result of fire suppression. Woody plant encroachment occurs after the grassland communities are degraded and the grass growth mechanisms and ecosystem biogeochemical processes are reduced to be nonfunctional as a result of traditional antagonistic management practices (Manske 2018).

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Table 1. Range in temperatures reached during prescribed burning of grassland and shrubland habitats.

	Grassland Habitat		Shrubland Habitat	
Backfire				
Soil surface Temperature	278.6°F	(137°C)	617°F	(325°C)
Range of fire Temperatures	199.4°-449.6°F	(93°-232°C)	399.2°-800.6°F	(204°-427°C)
Height of hottest Temperature	2 inches	(5 cm)	3.2 inches	(8 cm)
Headfire				
Soil surface Temperature	402.8°F	(206°C)	815°F	(435°C)
Range of fire Temperatures	199.4°-800.6°F	(93°-427°C)	449.6°-1299.2°F	(232°-704°C)
Height of hottest Temperature	6 inches	(15 cm)	3.2-7.9 inches	(8-20 cm)

Data from Bailey and Anderson 1980.

Table 2. Fire effects and Regeneration type of woody plants that encroach into Rangelands of the Northern Plains.

	Fire Effects				Regeneration Types	
Woody Plants	Total Plant Kill	Top Kill	Trunk Little Damage	Activates Vegetative Buds	Vegetative	Sexual
Common juniper	X				X	X
Creeping juniper	X				X	X
Rocky Mtn juniper	X					X
Ponderosa pine	X		X			X
American elm		X		X	X	X
Bur oak		X	X	X	X	X
Green ash		X	X	X	X	X
Balsam popular		X		X	X	X
Plains cottonwood		X		X	X	X
Quaking aspen		X		X	X	X
Peachleaf willow		X		X	X	X
Beaked willow		X		X	X	X
Coyote willow		X		X	X	X
Sandbar willow		X		X	X	X
Prairie willow		X		X	X	X
American hazelnut		X		X	X	X
Beaked hazelnut		X		X	X	X
Kinnikinnick		X		X	X	X
Juneberry		X		X	X	X
Northern hawthorn		X		X	X	X
Shrubby cinquefoil		X		X	X	X
Wild plum		X		X	X	X
Pin cherry		X		X	X	X
Sand cherry		X		X	X	X
Chokecherry		X		X	X	X
Prickley wild rose		X		X	X	X
Prairie wild rose		X		X	X	X

Table 2 (cont.). Fire effects and Regeneration type of woody plants that encroach into Rangelands of the Northern Plains.

	Fire Effects				Regeneration Types	
Woody Plants	Total Plant Kill	Top Kill	Trunk Little Damage	Activates Vegetative Buds	Vegetative	Sexual
Smooth wild rose		X		X	X	X
Western wild rose		X		X	X	X
White spiraea		X		X	X	X
Leadplant		X		X	X	X
False indigo		X		X	X	X
Dwarf wild indigo		X		X	X	X
Wild licorice		X		X	X	X
Silverberry		X		X	X	X
Buffaloberry		X		X	X	X
Fragrant sumac		X		X	X	X
Skunkbush		X		X	X	X
Western snowberry		X		X	X	X
Fourwing saltbush		X		X	X	X
Moundscale saltsage		X		X	X	X
Winterfat		X		X	X	X
Greasewood		X		X	X	X
Green sage		X		X	X	X
Fringed sage		X		X	X	X
White sage		X		X	X	X
Sand sagebrush		X		X	X	X
Silver sagebrush		X		X	X	X
Big sagebrush	X					X
Rubber rabbitbrush		X		X	X	X
Yellow rabbitbrush		X		X	X	X
Broom snakeweed		X		X	X	X
Great Plains yucca		X		X	X	X
Totals #	5	48	3	48	50	53
Percentage %	9.4	90.6	5.7	90.6	94.3	100.0

Table 3. Vegetative bud location of woody plants that encroach into Rangelands of the Northern Plains.

	Vegetative Bud Location							
Woody Plants	Root Crown	Stem Base	Rhizome	Stolon	Lateral Roots	Trunk	Bent Stem to Soil	No buds Present
Common juniper							X	X
Creeping juniper							X	X
Rocky Mtn juniper								X
Ponderosa pine								X
American elm		X			X			
Bur oak	X				X	X		
Green ash	X	X						
Balsam popular		X			X	X	X	
Plains cottonwood	X				X	X	X	
Quaking aspen					X			
Peachleaf willow	X					X	X	
Beaked willow	X	X					X	
Coyote willow	X	X			X		X	
Sandbar willow			X					
Prairie willow	X	X						
American hazelnut	X		X				X	
Beaked hazelnut			X					
Kinnikinnick	X	X		X		X	X	
Juneberry	X		X	X				
Northern hawthorn		X			X			
Shrubby cinquefoil	X						X	
Wild plum	X				X			
Pin cherry		X			X			
Sand cherry	X		X		X			
Chokecherry	X		X					
Prickley wild rose			X					
Prairie wild rose	X				X			

Table 3 (cont.). Vegetative bud location of woody plants that encroach into Rangelands of the Northern Plains.

	Vegetative Bud Location							
Woody Plants	Root Crown	Stem Base	Rhizome	Stolon	Lateral Roots	Trunk	Bent Stem to Soil	No buds Present
Smooth wild rose	X				X			
Western wild rose	X		X				X	
White spiraea	X		X					
Leadplant	X		X					
False indigo	X				X			
Dwarf wild indigo	X		X		X			
Wild licorice			X					
Silverberry		X	X	X				
Buffaloberry	X		X					
Fragrant sumac	X		X		X		X	
Skunkbush	X		X					
Western snowberry		X	X					
Fourwing saltbush	X	X	X			X		
Moundscale saltsage	X	X			X			
Winterfat	X	X						
Greasewood	X				X			
Green sage			X					
Fringed sage		X	X					
White sage		X	X					
Sand sagebrush		X						
Silver sagebrush		X	X		X		X	
Big sagebrush								X
Rubber rabbitbrush	X					X		
Yellow rabbitbrush		X				X		
Broom snakeweed	X					X		
Great Plains yucca		X	X					
Totals #	30	20	23	3	18	9	13	5
Percentage %	56.6	37.7	43.4	5.7	34.0	17.0	24.5	9.4

Table 4. Frequency % and canopy cover % of vegetation in unburned and burned western snowberry colonies from 24 years of annual April burn treatment.

	Frequency %		Canopy Cover %	
	Unburned	Burned	Unburned	Burned
Annual Forbs	0	0	0	0
Perennial Forbs	204	348	13.1	49.9
Grass and Sedge	207	437	67.4	109.8
Shrubs	68	112	16	7
Western snowberry	56	52	31	2

Data from Anderson and Bailey 1980

Table 5. Live biomass production of plant biotypes on the number of repeated burn treatments and percent change from nonburned control.

Plant Biotypes		No Burns 6 reps	One Burn 4 reps	Two Burns 4 reps	Three Burns 4 reps	Four Burns 3 reps
Grass						
Biomass	(lbs/ac)	411.61a	310.12a	762.75a	512.87a	861.51a
% change	(%)		-24.7	85.3	24.6	109.3
Sedge						
Biomass	(lbs/ac)	224.59b	362.93b	74.34b	238.58b	145.81b
% change	(%)		61.6	-66.9	6.2	-35.1
Forb						
Biomass	(lbs/ac)	255.33c	454.35c	445.14c	587.41c	266.49c
% change	(%)		78.0	74.3	130.1	4.4
Shrub						
Biomass	(lbs/ac)	806.83d	136.00d	237.09d	52.00d	39.57d
% change	(%)		-83.1	-70.6	-93.6	-95.1
Total Live						
Biomass	(lbs/ac)	1698.36e	1263.39e	1519.19e	1390.87e	1313.38e
% change	(%)		-25.6	-10.6	-18.1	-22.7

Data from Manske 2007

Means in the same row and followed by the same letter are not significantly different ($P<0.05$).

Table 6. Shoot frequency of plant biotypes on the number of repeated burn treatments and percent change from nonburned control.

Plant Biotypes		No Burns 6 reps	One Burn 4 reps	Two Burns 4 reps	Three Burns 4 reps	Four Burns 3 reps
Native Grass						
Shoot frequency	(%)	107.0a	194.3b	183.3ab	198.8b	208.3b
% change	(%)		81.6	71.3	85.8	94.7
Sedge						
Shoot frequency	(%)	56.7c	95.5d	97.0d	77.8cd	89.0cd
% change	(%)		68.4	71.1	37.2	57.0
Introduced Grass						
Shoot frequency	(%)	86.7e	46.3ef	31.8ef	53.5ef	30.3f
% change	(%)		-46.6	-63.3	-38.3	-65.1
Perennial Forbs						
Shoot frequency	(%)	120.5g	167.8h	125.5gh	137.5gh	125.7gh
% change	(%)		39.3	4.1	14.1	4.3
Weedy Forbs						
Shoot frequency	(%)	85.5i	92.5i	80.3ij	78.0ij	42.0j
% change	(%)		8.2	-6.1	-8.8	-50.9
Shrubs						
Shoot frequency	(%)	111.7k	71.0kl	58.5kl	62.0kl	46.7l
% change	(%)		-36.4	-47.6	-44.5	-58.2

Data from Manske 2007

Means in the same row and followed by the same letter are not significantly different (P<0.05).

Table 7. Shoot frequency of grasses on the seasonal period of burn treatments and percent change from nonburned control.

Plant Biotypes		No Burns 6 reps	Early Spring (mid-late Apr) 1 rep	Spring (May-mid Jun) 3 reps	Early Summer (mid Jun-Jul) 7 reps	Mid Summer (early-mid Aug) 4 reps
Native Grass						
Western wheatgrass						
Shoot frequency	(%)	15.5e	42.0e	13.7e	16.4e	19.5e
% change	(%)		170.1	-11.8	6.0	25.8
Blue grama						
Shoot frequency	(%)	8.0f	4.0f	39.3g	7.4f	14.8fg
% change	(%)		-50.0	391.6	-7.1	84.4
Sedge						
Shoot frequency	(%)	56.7c	39.0c	97.3d	93.4cd	90.8cd
% change	(%)		-31.2	71.6	64.7	60.1
Introduced Grass						
Smooth bromegrass						
Shoot frequency	(%)	17.5h	0.0h	2.3h	0.3h	2.3h
% change	(%)		-100.0	-86.7	-98.3	-87.1
Quackgrass						
Shoot frequency	(%)	7.8i	1.0i	0.0i	0.4i	2.8i
% change	(%)		-87.2	-100.0	-94.5	-64.7
Kentucky bluegrass						
Shoot frequency	(%)	59.5j	72.0j	21.3k	42.0j	37.3jk
% change	(%)		21.0	-64.2	-29.4	-37.3

Data from Manske 2007

Means in the same row and followed by the same letter are not significantly different ($P<0.05$).

Table 8. Shoot frequency of plant biotypes on the seasonal period of burn treatments and percent change from nonburned control.

Plant Biotypes		No Burns 6 reps	Early Spring (mid-late Apr) 1 rep	Spring (May-mid Jun) 3 reps	Early Summer (mid Jun-Jul) 7 reps	Mid Summer (early-mid Aug) 4 reps
Perennial Forbs						
Shoot frequency	(%)	120.5g	157.0g	116.7g	154.6g	127.8g
% change	(%)		30.3	-3.2	28.3	6.1
Weedy Forbs						
Shoot frequency	(%)	85.5h	129.0i	43.3h	79.3h	78.8h
% change	(%)		50.9	-49.4	-7.3	-7.8
Shrubs						
Shoot frequency	(%)	111.7j	15.0l	22.0l	81.7jk	63.3k
% change	(%)		-86.6	-80.3	-26.9	-43.3
Western Snowberry						
Shoot frequency	(%)	58.3a	5.0b	10.3b	33.4ab	21.5b
% change	(%)		-91.4	-82.3	-42.7	-63.1
Western Rose						
Shoot frequency	(%)	35.8c	8.0d	4.3d	41.7c	41.3c
% change	(%)		-77.7	-87.9	16.4	15.1
Silverberry						
Shoot frequency	(%)	17.3e	2.0f	7.3e	6.6e	0.5f
% change	(%)		-88.5	-57.7	-62.1	-97.1

Data from Manske 2007

Means in the same row and followed by the same letter are not significantly different (P<0.05).

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Undisturbed Management of Grassland Habitat Is Not A Biologically Sustainable Treatment

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The standard go to recommended grassland habitat management for wildlife, scarce plants, and precarious insects is the undisturbed treatment. This report scientifically explains why the undisturbed treatment of grassland habitat is not biologically sustainable in the Northen Plains.

Often times, livestock grazing is removed to protect a grassland ecosystem based on naive presumptions that livestock grazing causes damage to a grassland ecosystem or that they interfere with the life cycle of wildlife, scarce plants, and precarious insects. Livestock grazing is not what causes damage to grasslands; poor management of grazing livestock can cause serious damage to grasslands. The greatest antagonistic effects to a grassland ecosystem occur from undisturbed management concepts that rest grasslands from grazing defoliation. The term "rest" is a misnomer; resting a grassland does not cause revitalizations of crucial biological and ecological processes. Resting a grassland by withholding partial defoliation by grazing results in regression of ecosystem processes and biological growth mechanisms. Several negative changes occur relatively soon after grazing graminivores are removed from grasslands; the live root biomass of grasses decrease (Whitman 1974), standing dead leaves and litter accumulate (Brand and Goetz 1986), and ecosystem biogeochemical processes diminish (Manske 2011b).

The reduction of live root surface area causes a decrease in active root length for interaction with symbiotic rhizosphere organisms and causes a decrease in absorption of water and nutrients from the soil. Reduction of active root biomass and diminishment of grass plant health vigor result in a loss of resource uptake efficiency and a suppression of competitiveness of grass plants to take up mineral nitrogen, essential elements, and soil water (Kochy 1999, Kochy and Wilson 2000).

Grass plants produce double the quantity of leaf biomass than needed for normal plant growth and maintentance (Crider 1955, Coyne et al. 1995). Without grazing graminivores to remove the surplus herbage production, the standing leaf material accumulates rapidly and changes from an asset to a detriment. The accumulation of nondefoliated live and standing dead leaves of grasses reduce light penetration below native grass light saturation points (Peltzer and Kochy 2001). Native grasses have high light saturation points and require near full sunlight. Warm season grasses have higher light saturation points than cool season grasses (Kochy 1999, Kochy and Wilson 2000). Shading reduces native warm season grasses more than native cool season grasses. Introduced cool season domesticated grasses have lower light saturation points than native grasses, permitting domesticated grass to live in low light conditions. The accumulating standing dead leaves shade the lower leaves, increasing the rate of leaf senescence and reducing the rate of photosynthesis, causing a decrease in the supply of carbohydrates (Coyne et al. 1995) that results in a reduction in growth of leaves and roots (Langer 1972, Briske and Richards 1995). Grass leaves grown under shaded conditions become longer but narrower, thinner, and lower in weight (Langer 1972) than leaves in sunlight. Shaded grass plants shift to erect growth forms with a small number of tillers (Briske and Richards 1995). Lack of grazing reduces grass tiller densities by decreasing tiller development and increasing tiller mortality through shading (Manske 2013). After a few years, shading reduces the composition of native grass species in the ecosystem and increases the composition of shade-tolerant or shade-adapted replacement species, like smooth bromegrass and Kentucky bluegrass.

Standing dead material not in contact with soil does not decompose through microbial activity. Dead plant material on nongrazed treatments breaks down slowly over several years by leaching and weathering and builds up into a thick mulch layer. Thick mulch effectively blocks sunlight from reaching understory young grass leaves. Thick mulch modifies soil temperatures. Thick mulch ties up and holds organic nutrients above the soil surface preventing accession to the soil organic matter which limits nutrient cycling through biogeochemical processes increasing the deficiencies of essential elements causing great reductions in grass growth of leaves and roots. Thick mulch absorbs and holds precipitation for later evaporation preventing the water from infiltrating into the soil diminishing soil water to deficiency quantities (Wright and Bailey 1982, Manske 2000, 2011a).

The loss of active root length is a contributing factor in the reduction of rhizosphere biomass. The primary cause for the reduction in rhizosphere biomass is, however, the great reduction in the quantity of carbohydrate energy exudated from the grass roots into the rhizosphere zone. Without partial defoliation by grazing, only a small quantity of short carbon chain energy leaks from the grass roots into the rhizosphere; this low amount of simple carbon compounds is barely enough to sustain a very small rhizosphere microbe biomass. A small biomass of rhizosphere organisms function at greatly reduced rates of organic material decomposition, and can mineralize only small quantities of nitrogen and other essential elements (Anderson et al. 1981, Coleman et al. 1983, Curl and Truelove 1986, Klein et al. 1988, Whipps 1990).

Removal of partial defoliation for 13 years resulted in an increase of standing dead and litter, an increase of introduced domesticated grasses, a great decrease of native grasses, and an increase of all forbs with a decrease in desirable forbs (Manske 2012). The total dead biomass was 63.6% of the total herbage biomass (an increase of 300.3%), with standing dead at 26.9% and litter at 36.7%. Live herbage biomass was 36.4% of the total herbage biomass, with domesticated grass at 64.8% (an increase of 94.8%), cool season grasses at 2.7% (a decrease of 89.0%), warm season grasses at 0.6% (a decrease of 79.4%), upland sedges at 22.9% (a slight decrease of 1.5%), and all types of forbs at 9.0% (an increase of 56.3%). The rhizosphere biomass had decreased to 52.2 kg/m^3 which can mineralize less than 20% of the minimum quantity of mineral nitrogen needed at 100 lbs/ac (112 kg/ha).

Removal of partial defoliation by grazing for 75 years resulted in an excessive increase of standing dead and litter, a remarkable increase of woody shrubs and trees, an increase of introduced domesticated grasses, a severe reduction of native grasses, and a considerable decrease of desirable forbs (Manske 2013). The total dead biomass was 59.7% of the total herbage biomass (an increase of 263.6%), with standing dead at 11.1% and litter at 48.6%. Live herbage biomass was 40.3% of total herbage biomass, with domesticated grass at 79.6% (an increase of 106.1%), cool season grasses at 5.7% (a decrease of 80.0%), warm season grasses at 0.04% (a decrease of 99.7%), upland sedges at 6.3% (a decrease of 23.9%), and all types of forbs at 8.4% (an increase of 20.0%). The woody shrubs and trees had increased 500.0% and occupied 53.8% of the land area. The grass root biomass had decreased 32.6%. The available mineral nitrogen was only at 42.0 lbs/ac (47.0 kg/ha) which is greatly below the needed minimum of 100 lbs/ac (112 kh/ha).

The huge increase of woody shrubs and trees was not caused by the lack of fire. It was caused by the lack of biologically effective grazing management that resulted in the great reduction of the grass plant mechanism of competitive nutrient and water resource uptake. When grass plants are managed biologically they become healthy and have the full competitive resource uptake mechanism working, seedlings of trees, shrubs, forbs, and introduced grasses cannot become established in mixed grass prairie communities (Li and Wilson 1998, Kochy and Wilson 2000, Peltzer and Kochy 2001).

With continued ecosystem degradation, the impeded native grasses declined further in their ability to be competitive in uptake of belowground resources of soil water and nutrients (Li and Wilson 1998, Kochy and Wilson 2001), causing additional mortality of native grasses and decreased density, resulting in the creation of numerous shaded bare spaces in the previously closed prairie plant communities (Manske 2013).

Opportunistic introduced cool season domesticated grasses, like Kentuck bluegrass and smooth bromegrass can exist under low light conditions and invade the shaded bare spaces by procuring the remaining belowground resources not being taken up by the diminutive, low vigor native grasses (Kochy and Wilson 2000). These domesticated grasses also have labile roots that breakdown easily making the nutrients contained in dead material readily available to support continued growth and expansion of these nonnative grasses without assistance from soil microorganisms. In a short period of time, the introduced domesticated grasses increase in density and herbage biomass creating greater shading problems for the suppressed native grasses, escalating degradation of an already devastated ecosystem.

With the removal of partial defoliation by grazing there is a great reduction in the quantity of carbohydrates exuded from the grass roots into the rhizosphere zone. The rhizosphere microorganism biomass and activity are dependent on access to outside sources of simple carbon chains from the grasses. The rhizosphere microflora trophic levels lack chlorophyll and have low carbon (energy) content. Partial defoliation of grass plants at vegetative phenological growth stages by large graminivores cause great quantities of exudates containing simple carbon compounds to be released through the plant roots into the rhizosphere zone. When that source of carbon stops, the small amount of carbon compounds in the plant material that leaks from grass roots is barely enough to sustain a very small rhizosphere biomass that cannot mineralize the minimum quantity of 100 lbs/ac of mineral nitrogen causing great reductions in herbage biomass production.

Grazing graminivores perform several indispensable functions for grassland ecosystems. Partial defoliation by grazing graminivores activate the four major internal grass plant growth mechanisms, enhance rhizosphere microorganisms activity and increase their biomass large enough to perform the ecosystem biogeochemical processes and to mineralize greater than 100 lbs/ac of mineral nitrogen plus the other essential elements, and they remove the surplus grass leaf biomass produced by grass plants before it can become a detriment to the ecosystem each growing season.

Grazing graminivores is biologically beneficial for grass plants and for grassland ecosystems when grazing periods are coordinated with grass phenological growth stages. The four primary physiological growth mechanisms within grass plants that perform the herbage replacement processes are activated with partial defoliation by grazing graminivores when 25% to 33% of leaf weight is removed from 60% to 80% of lead tillers during vegetative phenological growth stages between the three and a half new leaf and the flower stage when a threshold quantity of 100 lbs/ac of mineral nitrogen is available. Unavailable soil organic nitrogen must be mineralized by soil microbes in order for nitrogen to be usable by grass plants. A large biomass of rhizosphere microorganisms is required to mineralize a large quantity of nitrogen yielding 100 lbs/ac. Grassland microbes are achlorphyllous and cannot fix their own carbon energy. Large quantities of surplus short chain carbon energy are produced by healthy vegetative lead tillers that can be exudated into the microbial rhizosphere when 25% to 33% of the leaf weight is removed with partial defoliation by grazing graminivores while lead tillers are between the three and a half new leaf stage and the flower stage. The four primary physiological growth mechanisms are not functional when less than 100 lbs/ac of mineral nitrogen is available and are not activated when zero % or greater than 33% of the leaf weight of lead tillers is removed during vegetative growth stages.

Grazing graminivores receive nutritious forage from healthy grass plants. However, providing forage for graminivores is not the only purpose for grazing grasslands. Grass plants have biological requirements and have four primary physiological growth mechanisms that must be activated by partial defoliation by grazing. Rhizosphere microorganisms are needed in large quantities to perform all of the ecosystem biogeochemical processes, but are unable to fix carbon energy and require exudated short chain carbon energy that can be provided by partial defoliation by grazing. The three indispensable biotic components of grasslands; grass vegetation, rhizosphere organisms, and large graminivores; must have their biological requirements provided with partial defoliation by grazing graminivores in order for grassland ecosystems to function at achievable levels.

The successful sustainability of grassland ecosystems depends upon the implementation of biologically effective management strategies that can provide the biological and physiological requirements of the forage grass plants, soil microorganisms, and grazing graminivores, that can activate and maintain the grass plant growth mechanisms and the ecosystem biogeochemical processes, that can revitalize soil structure and functionality, that can increase forage growth and nutritional quality, and that can improve livestock growth and weight performance along with the capture of greater wealth per acre.

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Deferred-Rotation: An Obsolete Grazing Practice

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The current science of rangeland management has been built by countless, hardworking, dedicated scientists that have inspired deeper investigations into how rangeland ecosystems work. The concept of deferred and rotation grazing was developed on an early hypothesis that considered the only process to improve degraded native rangeland was to reseed the land by mechanical methods or by letting the grass plants produce seeds and trample the seeds into the ground with livestock (Jardine 1916). Modern more profound hypothesis consider improvement of degraded native rangeland by activating the processes of vegetative reproduction of secondary tillers from axillary buds and by increasing the biomass of the symbiotic rhizosphere microorganisms that perform the ecosystem biogeochemical processes (Manske 2018) making the deferred-rotation grazing practices obsolete.

Vegetative tiller growth is the dominant form of reproduction in semiarid and mesic grasslands (Belsky 1992, Chapman and Peat 1992, Briske and Richards 1995, Chapman 1996, Manske 1999a) not sexual reproduction and the development of seedlings. Recruitment of new grass plants developed from seedlings is negligible in grassland ecosystems. The frequency of true seedlings is extremely low in functioning grasslands, and establishment of seedlings occurs only during years with favorable moisture and temperature conditions (Wilson and Briske 1979, Briske and Richards 1995), in areas of reduced competition from vegetative tillers, and when resources are readily available to the growing seedling.

The deferred-rotation grazing system was developed by Arthur Sampson from research conducted in the Blue Mountains of Oregon. The first version was a two pasture system with one pasture grazed early and one pasture deferred until late season, then rotated the order on a one or two year cycle (Sampson 1913). The second version was a three pasture system with grazing separated into spring, summer, and fall. The sequence was followed for two years, during the rotation cycle, the fall pasture became the spring pasture, the previous spring pasture became the summer pasture, and the previous summer pasture became the fall pasture (Sampson 1923). The intended purpose of deferment was to gain plant vigor, increase seed production, storage of carbohydrates in roots and stems, and improve the health of rangeland. Grazing after seed maturity would scatter and trample the seeds into the soil in order to promote seedling establishment. The second year of deferment was intended to improve development of young seedlings.

Two years of deferment was explained by Sampson (1914), “The grazing has been deferred until the fall for two years. This is done to allow any seedlings that might start from the previous year’s seeding a chance to become more firmly established before the division (pasture) is grazed.”

Sampson (1913, 1914) and Jardine (1916) knew that grass seed that drops from the grass head and germinate have an extremely low survival rate because they do not get enough root material into the soil before they dry out. So the late season trampling by cattle seemed to be the only logical way to get the dropped seeds too the soil. They did not think one year would be enough, so they extended the process to two years.

The Blue Mountains of Oregon where Sampson collected data is spectacular country, however, the seasonal precipitation distribution is the Pacific Pattern with most of the precipitation occurring during fall and winter. The fall rains begin in late September and increase with a peak in November or December and decrease to March, with July, August, and early September receiving very little precipitation. This pattern greatly limits available soil moisture for developing grass roots during the growing season. Sampson would have experienced very little grass growth and nearly no grass regrowth during the summer months. The grasses of Oregon produce vegetation tillers, but because of the lack of rainfall during summer, they are usually inhibited by low soil water to grow during that growing season. The grazing activated vegetative secondary tillers appear the next spring, a month or more ahead of normal lead tiller development. Sampson did not recognize these early spring tillers as last grazing season stimulated vegetative tillers. At that time, pasture scientists, were trained as agronomists, knew that some grasses produced vegetative tillers. However, the importance of vegetative tillers was dismissed. Grass seed production and seedling establishment was far more important for the improvement of pasture forage production according to the agronomic based scientific concepts of the time.

A deferred and rotation grazing treatment was investigated at the Northern Great Plains Field Station at Mandan, North Dakota (Sarvis 1923, 1941). The experimental plan followed closely, with modifications, to the grazing order of a three pasture deferred and rotation practice described in the 1915 Agricultural Yearbook (Jardine 1916). This deferred-rotation treatment was added to the two year old stocking rate on seasonlong grazed pastures study that had four rates of grazing intensities. These grazing investigations were conducted by J.T. Sarvis for 23 years from 1918 to 1940. The modifications made by Sarvis (1923) was the change in the pasture sequence of the pasture with the fall deferred treatment moved to the summer period, which was different than Sampson's plan which moved the fall deferred treatment to the spring period (Sampson 1923).

Sarvis (1941) believed that undergrazing caused slight deterioration to plant communities by the accumulation of old vegetation that steers would not eat and by the increase of coarseness of weeds. Sarvis (1941) also knew that continued removal of the maximum quantity (100%) of the annual forage produced would sooner or later cause a sharp decline in grazing capacity. As a result, Sarvis developed grazing guidelines that required that 15% to 25% of the annual forage production to remain standing at the end of the grazing season. However in practice, the reported mean forage use on the deferred pastures was 92% removed and the mean forage use on the standard seasonlong pasture was 77% removed (Sarvis 1923).

The grazing investigations conducted by J.T. Sarvis (1923, 1941) at the Mandan, North Dakota, Northern Great Plains Field Station studied the three pasture deferred and rotation grazing treatment that was developed by Sampson (1913, 1923), and adapted and put into practice by the US. Forest Service (Jardine 1916), in order to determine the performance of its direct application in the northern Great Plains. The study area was a large section of flat land with very good soil and uniform mixed grass prairie in excellent condition, 3.5 miles south of Mandan. Seventy acres were divided into three equal pastures to be grazed during spring, summer, and fall periods. A comparable control treatment was seventy acres in one pasture grazed seasonlong. The intended grazing season was 150 days from mid May to mid October (table 1). The research animals were two years old grade steers of standard beef breeds of Angus, Herefords, and Shorthorns that were furnished by the North Dakota Agricultural Experiment Station with the mean initial weight of 750 pounds.

When the steers on the grazing treatments appeared to have lost weight, they were weighed at 5 or 10 day intervals and when the weight loss was documented the steers on the seasonlong treatments were removed from the study pastures and moved to the reserve pasture. When forage on the fall pasture of the deferred treatment became short and inferior and the steers began to lose weight, the steers were moved to the spring pasture that had new secondary growth (Sarvis 1941). This new secondary growth was not recognized as vegetative reproduction of tillers from axillary buds.

During the first two years of the deferred treatment, 10 steers grazed the deferred and seasonlong treatments at the same stocking rate. However, the steers on the deferred treatment gained a mean of only 260 pounds which was much less weight than the steers on the seasonlong treatment that gained a mean of 309 pounds. The number of steers placed on the deferred treatment was increased to an average of 14 head and the number of steers on the seasonlong treatment remained at 10 head. However, after 17 years the mean weight gain per head on the deferred treatment reached 266.1 pounds and the gain per head on the seasonlong treatment dropped to 308.3 pounds (table 2).

The lower weight gain for the steers on the deferred treatment (table 3) were explained by Sarvis (1923), "The deferred and rotation pastures show either light gains or losses for the month of October and somewhat reduced gains during September. The lower gains during the latter part of the season do not necessarily condemn fall grazing. This is the time when cattle put on the "finish" so often referred to by stockmen, which is apparently a hardening process brought about through a reduction in the quantity of water that they drink, as well as a change in the condition of their flesh. Therefore, when cattle are without feed or water for 24 hours in the fall they will "shrink" less than they would during the same length of time earlier in the season. The autumn also represents the transition or adjustment period of the cattle between summer and winter. The cooler weather of autumn always causes shrinkage of the cattle, which is recorded as a loss in weight."

Sarvis failed to explain why the steers on the seasonlong treatment did not experience the same degree of "finish" as the steers on the deferred pasture (table 3).

Sarvis (1923) explained the purpose of the deferment, "This deferred and rotation grazing system is designed to allow each division of the pasture to mature a crop of seeds for two successive years before it is harvested by the cattle in the fall of each year. Grazing on each division is deferred and rotated, so that each unit has an equal chance to produce a maximum crop of seeds normally before it is disturbed by grazing. The seeds of the grasses which are scattered on the ground are aided in their planting by trampling of the cattle.

Sarvis (1941 p.80) concluded, "So far as it has been possible to determine, there has been no significant benefit from reseeding of the grasses under this deferred and rotation grazing system during this experiment after 23 years."

Sampson knew very early in his studies that cattle produced very low weight gains on the deferred pastures, he knew that some grasses reproduced vegetatively, and he did not have documentation that the production of seeds resulted in greater numbers of seedlings.

The US Forest Service knew that cattle produced very low weight gains on the deferred pastures, and they did not have documentation that the production of seeds resulted in greater numbers of seedlings.

Sarvis knew in the first two years of study that two year old steers produced very low weight gains on the deferred pastures, he documented that the number of seedlings did not increase on the deferred treatment, and he documented a large reduction in grass density that he attributed to the severe drought frequency during the study period with 4 of the driest years recorded including 1934 and 1936. Sarvis did not consider the high forage use at 85% to 75% to be a factor in grass density reduction.

Despite the lack of supporting scientific data, these pasture agronomists still continued to promote the use of the deferred-rotation grazing practice to livestock producers west of the Mississippi River.

The deferred-rotation grazing practice was included in a study of the effects of grazing management practices on grassland vegetation and on the quantity of prairie grouse concealment cover of the Sandhills region in southeastern North Dakota that evaluated for visual obstruction by the height-density pole, herbage biomass by hand clipping, and basal cover by the ten pin point frame conducted by Manske, 1975 to 1980.

The seasonlong grazing treatment resulted in a mean 100% VOM of the switchgrass zone at 1.5 dm (5.9 in) with 55% readings at or above 1.5 dm during spring, 13% of the herbage biomass samples from the Upland and Midland communities were greater on the grazed area than on the ungrazed area, and the plant species composition significantly increased with Kentucky bluegrass, and decreased with warm and cool season native grasses.

The deferred grazing treatment resulted in a mean 100% VOM of the switchgrass zone at 1.6 dm (6.3 in) with 62% readings at or above 1.5 dm during spring, 20% of the herbage biomass samples from the Upland and Midland communities were greater on the grazed area than on the ungrazed area, and the plants species composition significantly increased with Kentucky bluegrass, and decreased with switchgrass, warm and cool season native grasses, and upland sedges.

The twice-over rotation grazing strategy resulted in a mean 100% VOM of the switchgrass zone at 2.0 dm (7.9 in) with 78% readings at or above 1.5 dm during spring, 32% of the herbage biomass samples from the Upland and Midland communities were greater on the grazed area than on the ungrazed area, and plant species composition significantly increased with switchgrass, lowland sedges, warm and cool season native grasses, upland sedges, and total basal cover.

Grassland ecosystems of the Sandhills region were negatively affected by the deferred grazing practice from the significant yearly increase in Kentucky bluegrass and a decrease in native warm and cool season grass basal cover, total grass density, herbage biomass production, and low quality of prairie grouse concealment cover. The grassland ecosystems received a huge loss of significant energy and resources which were used for the increased useless grass seed production that could have been supplied for an increase of vegetative secondary tiller production with adequate crude protein for lactating cows to graze until mid October.

Deferring the starting date of grazing on native rangeland until after the grass lead tillers have flowered and developed seeds prevents stimulation of compensatory physiological mechanisms, vegetative reproduction by tillering, competitive nutrient resource uptake, and water use efficiency mechanisms within grass plants, and rhizosphere organism activity that perform all of the ecosystem biogeochemical processes. The herbage biomass available to grazing livestock on deferred grazing practices is below the potential quantities (Manske 2000b) and the nutritional quality is below the crude protein requirements of lactating cows (Whitman et al. 1951, Manske 1999b) because of leaf senescence and translocation of cell constituents from leaf structures (Langer 1972, Beard 1973, Leopold and Kriedemann 1975). The intended biological purpose of deferred grazing was to increase grass density by promoting seedling development from increased seed stalk quantities and to use trampling by livestock to scatter and plant the produced seeds. However, grassland ecosystem processes do not function in accordance with the obsolete deferred grazing hypothesis.

Effects on cow and calf weight performance from three grazing management strategy concepts were evaluated for five years (1983-1987) in western North Dakota on native rangeland mixed grass prairie conducted by Manske.

The old management concept of deferred grazing until after seed set was stocked heavily at 8.88 ac/AU and 2.22 ac/AUM for 4.0 months from 16 Jul to 15 Nov (122 days) (table 4).

The traditional concept of seasonlong grazing was stocked at 12.31 ac/AU and 2.80 ac/AUM for 4.39 months from 18 Jun to 30 Oct (134 days) (table 4).

The biologically effective concept of three pasture twice-over rotation strategy was stocked at 10.22 ac/AU and 2.28 ac/AUM for 4.49 months from 1 Jun to 16 Oct (137 days) (table 4).

On the deferred treatment, calf weight gain was only at 1.80 lbs per day, 24.73 lbs per acre, and accumulated weight gain was low at 219.60 lbs per head. Cow weight gain was extremely low at 0.06 lbs per day, 0.82 lbs per acre, and accumulated weight gain was 7.24 lbs per head (tables 5 and 6).

On the traditional seasonlong treatment, calf weight gain was 2.18 lbs per day, 23.77 lbs per acre, and accumulated weight gain was 292.12 lbs per head. Cow weight gain was 0.40 lbs per day, 4.35 lbs per acre, and accumulated weight gain was 53.60 lbs per head (tables 5 and 6).

On the biologically effective twice-over strategy, calf weight gain was 2.21 lbs per day, 29.63 lbs per acre, and accumulated weight gain was 302.80 lbs per head. Cow weight gain was 0.62 lbs per day, 8.31 lbs per acre, and accumulated weight gain was 84.91 lbs per head (tables 5 and 6).

Dollar value captured on the deferred treatment was the lowest. Pasture cost was low at $77.79 and cost per day was low at $0.64 because of the very heavy stocking rate (table 4). Pasture weight gain value was low at $153.72, net return per cow-calf pair was very low at $75.93 because of the low calf weight gain, net return per acre was moderate at $8.55 because of the heavy stocking rate, and the cost per pound of calf weight gain was high at $0.51 per lb because of the low calf gains (tables 5 and 6).

Dollar value captured on the traditional seasonlong treatment was moderate. Pasture cost was high at $107.84 and cost per day was high at $0.80 because of the low stocking rate (table 4). Pasture weight gain value was high at $204.48, net return per cow-calf pair was high at $96.64, net return per acre was low at $7.85 because of the low stocking rate, and the cost per pound of calf weight gain was low at $0.37 per lb because of the good calf gains (tables 5 and 6).

Dollar value captured on the biologically effective twice-over strategy was good. Pasture cost was moderate at $89.53 and cost per day was low at $0.65 (table 4). Pasture weight gain value was high at $211.96, net return per cow-calf pair was very high at $122.43, and net return per acre was very high at $11.98, and the cost per pound of calf weight gain was very low at $0.30 per lb (tables 5 and 6).

The crude protein content of grass lead tillers drops below the requirements of a lactating cow during the last two weeks of July (Whitman et al. 1951, Manske 1999b). The cow weight gain per day begins to decrease during early August on the deferred and seasonlong grazing practices (table 6) and those cows lose weight after mid September. The calf weight gain per day begins to decrease two week after their cows decrease in weight gain on the deferred and seasonlong grazing practices (table 6).

The grazing cows on the twice-over rotation strategy stimulate vegetative reproduction of secondary tiller development from the axillary buds during the first grazing period from 1 June to 15 July. These secondary tillers provide adequate crude protein to meet the lactating cows requirements through September on table 6. During these early years of development of the twice-over system, it was hypothesized that the tiller stimulation period lasted until the end of July. It did not, it lasts until mid July. As a result the third pasture did not grow secondary tillers and the cows lost weight during early October (table 6). When the stimulation period was adjusted to mid July, the third pasture produced secondary vegetative tillers high in crude protein, and the cows gained weight until mid October. Mid October is the latest that grass plants can be pushed to maintain adequate levels of crude protein that meets lactating cow requirements. Notice the jump in cow and calf weight gain on the twice-over practice in early August when the old second grazing period previously started. With the adjustment in the stimulation period, the first grazing period on all pastures is 45 days long from 1 June to 15 July and the second period is 90 days long from 15 July to 14 October. The grassland ecosystem improves and cow and calf weight gains increase because of the grazing stimulated vegetative reproduction of secondary tillers from axillary buds that contain adequate quantities of crude protein to meet the requirements of lactating cows until mid October.

Biologically effective management of native rangeland meets the biological and physiological requirements of the grass plants, soil organisms, and grazing animals, and cycles the essential elements. The biologically effective twice-over rotation grazing management strategy coordinates defoliation events with grass phenological growth stages and activates the compensatory physiological mechanisms, the vegetative reproduction by tillering mechanisms, the nutrient resource uptake mechanisms, and the water use efficiency mechanisms within grass plants, and elevates the soil rhizosphere microorganism biomass that perform all of the ecosystem biogeochemical processes.

An early hypothesis that had a biologically incomplete concept of how grassland ecosystems function required reseeding to restore degraded grasslands was used to develop the deferred-rotation grazing practice. However, the concept that recruitment of new plants on grassland ecosystems comes from seedlings was obsolete. New grass plants develop from vegetative secondary tillers. Because of the early pasture scientists dismissed the importance of vegetative tillers, the deferred grazing practices caused further ecosystem degradation and poor livestock weight gains. The deferred practices does not increase grass seedling establishment, and vegetative tillers are inhibited, causing a decrease in native grass density, providing spaces for Kentucky bluegrass and other weeds to increase. The resulting available late season forage is senescent lead tillers, dried Kentucky bluegrass, and coarse mature weeds that contain crude protein at levels well below the requirements of lactating cows causing extremely poor weight gain performances fromcows and calves.

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Table 1. Summer grazing period, stocking rate, and pasture costs (rent at $8.76/ac) on the deferred and seasonlong treatments conducted by J.T. Sarvis, 1918-1934.

Management Strategy Concept	Grazing Period	# Days	# Months	Acres per 2 yr Steer	Acres per Month	Pasture Cost $	Cost per day $
Deferred	16 May-8 Oct	146	4.79	5.0	1.04	43.80	0.30
Seasonlong	16 May-10 Oct	148	4.85	7.0	1.44	61.32	0.41

Based on Data from Sarvis 1941.

Table 2. Summer two year old steer weight performance and net returns (at market value of $0.70/lb) on the deferred and seasonlong treatments conducted by J.T. Sarvis, 1918-1934.

Management Strategy Concept	Gain per Head lbs	Gain per Day lbs	Gain per Acre lbs	Pasture Weight Gain Value $	Net Return per Steer $	Net Return per Acre $	Cost/lb Steer Gain $
Deferred							
Steer	266.1	1.82	53.2	186.27	142.47	28.49	0.17
Seasonlong							
Steer	308.3	2.08	44.0	215.81	154.49	22.07	0.20

Based on Data from Sarvis 1941.

Table 3. Two year old steer gain per head and gain per day during grazing season on native rangeland managed by deferred and seasonlong treatments conducted by J.T. Sarvis, 1918-1934.

2 yr Steer	16 May-30 Jun Spring	1 Jul-31 Aug Summer	1 Sep-15 Oct Fall	16 May-15 Oct Season
Deferred				
Gain/Head	135.8	110.5	19.8	266.1
Gain/Day	2.95	1.78	0.44	1.82
Seasonlong				
Gain/Head	154.5	119.2	34.6	308.3
Gain/Day	3.36	1.92	0.77	2.08

Data from Sarvis 1941.

Table 4. Summer grazing period, stocking rate, and pasture costs (rent at $8.76/ac) on the deferred, seasonlong, and twice-over treatments in western North Dakota conducted by L.L. Manske, 1983-1987.

Management Strategy Concept	Grazing Period	# Days	# Months	Acres per C-C pr	Acres per AUM	Pasture Cost $	Cost per Day $
Deferred	16 Jul-15 Nov	122	4.0	8.88	2.22	77.79	0.64
Seasonlong	18 Jun-30 Oct	134	4.39	12.31	2.80	107.84	0.80
Twice-over	1 Jun-16 Oct	137	4.49	10.22	2.28	89.53	0.65

Table 5. Summer calf and cow weight performance and net returns (at market value of $0.70/lb) on the deferred, seasonlong, and twice-over treatments in western North Dakota conducted by L.L. Manske, 1983-1987.

Management Strategy Concept	Gain per Head lbs	Gain per Day lbs	Gain per Acre lbs	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Cost/lb Calf Gain $
Deferred							
Calf	219.60	1.80	24.73	153.72	75.93	8.55	0.51
Cow	7.24	0.06	0.82				
Seasonlong							
Calf	292.12	2.18	23.73	204.48	96.64	7.85	0.37
Cow	53.60	0.40	4.35				
Twice-over							
Calf	302.80	2.21	29.63	211.96	122.43	11.98	0.30
Cow	84.91	0.62	8.31				

Table 6. Calf and cow gain per day during biweekly periods grazing native rangeland managed by three systems in western North Dakota conducted by L.L. Manske, 1983-1987.

Calf	Jun		Jul		Aug		Sep		Oct		Nov	
Deferred				2.39	2.39	2.23	2.09	2.09	1.04	0.77	0.77	
Seasonlong		2.52	2.50	2.22	2.34	2.44	2.30	1.87	1.61	1.40		
Twice-over	2.61	2.06	2.25	2.27	2.55	2.50	2.18	2.06	1.44			
Cow	**Jun**		**Jul**		**Aug**		**Sep**		**Oct**		**Nov**	
Deferred				1.52	1.49	0.71	0.15	-0.19	-0.55	-0.74	-1.01	
Seasonlong		1.97	1.78	1.10	0.95	0.20	0.07	-0.38	-0.81	-0.74		
Twice-over	3.04	2.17	0.70	0.52	0.79	0.89	0.84	0.54	-1.68			

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Weed Control Without Change of Grassland Management

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Weed intrusion into Northern Plains grassland ecosystems has usually been superficially considered to be by forceful, aggressive, invader plants that become established by dislodging the desirable native grass plants. Except, the invasion of these problematical unwanted weeds cannot occur without the previous creation of open spaces in grassland communities from antagonistic management practices. The presence of weedy plants in grassland communities are the visual symptoms of degraded grassland ecosystems; invading weeds are not the cause of degradation of the grasslands. Prescribed control treatments designed to reduce the weedy species can temporarily decrease the quantity of weeds, but weed reduction cannot restore the problems of deteriorated ecosystems. Degraded grassland ecosystems continue to remain susceptible to reinfestation of undesirable weeds. Restoration of the degraded grassland ecosystems requires that the old style management practices be changed to biologically effective strategies (Manske 2018e).

Degradation of grassland ecosystems occurs as a result of antagonistic traditional management practices (Whitman 1974) that diminish the rhizosphere microorganism biomass by preventing the surplus short chain carbon energy produced in grass lead tillers from being exudated through the roots into the rhizosphere upon which the soil organisms depend for growth and development (Manske 2011b). Diminishment of the biomass of rhizosphere microbes severely reduces the quantity of soil organic nitrogen to be mineralized (Coleman et al. 1983, Klein et al. 1988). This management caused deficiency of soil mineral nitrogen below 100 lbs/ac, typically around 50 lbs/ac, causes great reductions in native grass herbage biomass production (Wight and Black 1972, 1979) and causes decreases in native grass density (basal cover) creating numerous bare spaces between grass plants. The open spaces are ideal habitat for invasion of opportunistic introduced grasses, weedy forbs, and woody shrubs and trees. The degree of the aboveground grass species deterioration lags behind the degree of degradation of the belowground ecosystem biogeochemical processes performed by the rhizosphere microorganisms (Manske 2011b).

Intrusive weeds can only become established in grasslands after the ecosystem has been degraded by poor grazing practices, no grazing (idle), fire, and drought conditions. Seedlings or rhizomes of trees, shrubs, weedy forbs, and introduced grasses cannot become established in grassland ecosystems containing healthy grass plants (Peltzer and Kochy 2001) with full functionality of the nutrient resource uptake competitiveness mechanism (Manske 2018a, c).

Management of grasslands has traditionally been designed to provide forage for livestock and stewardship for the aboveground portions of the grass plants. Grassland ecosystems are much more complex than the traditional concept. Maintenance of grassland ecosystem structure and function necessitates that management practices meet the biological and physiological requirements of grass plants and soil microorganisms, and the nutrient requirements of domesticated cattle. These three fundamental interactive biotic components are indispensable for full functionality of grassland ecosystems (Manske 2011a).

Grazing livestock depend on grass plants for nutritious forage. Grass plants depend on rhizosphere soil microorganisms for mineralization of essential elements from the soil organic matter. Rhizosphere organisms, which are achlorophyllous, depend on grass plants for short carbon chain energy that is exudated through the roots of lead tillers at vegetative growth stages following partial defoliation by grazing livestock. Grass plants produce double the leaf biomass than is needed for photosynthesis in order to attract the vital partial defoliation by grazing livestock on which they depend (Manske 2018a).

Grass plant growth and development of replacement tissue depend on four internal physiological grass growth mechanisms that are: compensatory physiological mechanisms, vegetative reproduction by tillering, water use efficiency, and nutrient resource uptake competitiveness (Manske 2018a, c).

The compensatory physiological mechanisms give grass plants the capacity to replace lost leaf and shoot biomass following grazing by increasing meristematic tissue activity, increasing photosynthetic capacity, and increasing allocation of carbon and nitrogen (McNaughton 1979, 1983, Briske 1991). Fully activated mechanisms can produce replacement foliage at 140% of the weight that was removed during grazing (Manske 2009).

Vegetative secondary tillers are shoots that develop on lead tillers from growth of axillary buds and the subsequent development of vegetative tillers is regulated by auxin, a growth-inhibiting hormone produced in the apical meristem and young leaves. Partial defoliation of young leaf material at vegetative growth stages temporarily reduces the quantity of auxin which then allows cytokinin, a growth hormone, to stimulate the meristematic tissue of multiple axillary buds to develop into vegetative secondary tillers (Mueller and Richards 1986, Richards et al. 1988, Murphy and Briske 1992, Briske and Richards 1994, 1995).

Water use efficiency in grass plants is not at a single constant rate. Precipitation (water) use efficiency of grass plants improves when soil mineral nitrogen is available at threshold quantities of 100 lbs/ac (112 kg/ha) and greater. The inhibitory deficiencies of mineral nitrogen on grasslands that have less than 100 lbs/ac of available soil mineral nitrogen cause the weight of herbage production per inch of precipitation received to be reduced an average of 49.6% below the weight of herbage produced per inch of precipitation on the grassland ecosystems that have greater than 100 lbs/ac of mineral nitrogen (Wight and Black 1972, 1979).

Nutrient resource uptake competitiveness mechanism determines the level of grass plant dominance within a grassland community. Removal of aboveground leaf material from grass plants affects root functions. Removal of 50% or more leaf material greatly reduces root growth, root respiration, and root nutrient and water absorption resulting in severe degradation of the functionality of grass plants (Crider 1955). Reduction of active root biomass causes diminishment of grass plant health and vigor (Whitman 1974) that result in a loss of resource uptake efficiency and a suppression of the competitiveness of grass plants to take up mineral nitrogen, essential elements, and soil water. Reduction of grass plant nutrient uptake competitiveness allows successful establishment of undesirable grasses, weedy forbs, and shrubs and tree seedlings and rhizomes into grassland communities (Li and Wilson 1998, Kochy 1999, Kochy and Wilson 2000, Peltzer and Kochy 2001).

Activation of these physiological grass growth mechanisms requires partial defoliation by grazing animals that remove 25% to 33% of leaf weight from 60% to 80% of lead tillers coordinated at vegetative phenological growth stages between the three and a half new leaf stage and the flower stage when a threshold quantity of 100 lbs/ac (112 kg/ha) of mineral nitrogen is available (Manske 1999, 2018e). These grass growth mechanisms function at remarkably high rates on grasslands that have greater than 100 lbs/ac of available mineral nitrogen and these mechanisms do not function or function at extremely low rates on grasslands that have mineral nitrogen deficiencies at less than 100 lbs/ac (Manske 2009, 2014, 2018d).

Soil organic nitrogen is unavailable to plant growth and must be mineralized by soil microbes in order for nitrogen to be usable by grass plants. A large biomass of rhizosphere microorganisms is required to mineralize a large quantity of nitrogen yielding 100 lbs/ac. Grassland microbes are achlorophyllous and cannot fix their own carbon energy. Large quantities of surplus short chain carbon energy are produced by healthy vegetative lead tillers that can be exudated into the microbial rhizosphere when 25% to 33% of the leaf weight is removed with partial defoliation by grazing animals while lead tillers are between the three and a half new leaf stage and the flower stage (Manske 2018a). A high rhizosphere microbe biomass of 214 to 406 kg/m^3 (363 to 689 lbs/yd^3) can mineralize 111.3 to 176.3 kg/ha (99.4 to 157.4 lbs/ac) of mineral nitrogen (Manske 2018d) and will require 3 to 6 growing seasons with biologically effective grazing management to develop depending on degree of ecosystem degradation (Manske 2018e).

A large biomass of rhizosphere microorganisms can perform all of the grassland ecosystem biogeochemical processes that renew nutrient flow activities in intact grassland soils. Biogeochemical processes transform stored essential elements from organic forms into plant-usable inorganic forms. Biogeochemical processes also capture replacement quantities of lost or removed major essential elements of carbon, hydrogen, nitrogen, and oxygen, with assistance from active live plants, and transform the captured major essential elements into storage as organic forms for later use. And the biogeochemical processes also decompose complex unusable organic material into compounds and then into reusable essential elements (Manske 2018a).

The plants considered to be native or indigenous to the Northern Plains did not originate in this region. All of these plants originated in numerous other regions and migrated here by different mechanisms and at different times and rates. The Northern Plains region was effectively devoid of vegetation during the two million year glaciation period. Towards the end of the ice age, around 10,000 years ago, a sudden climate change accelerated melting of the glacial ice, and exposed the underlying mineral dirt, thereafter, extant plants were able to advance into the Northern Plains. A climate change to conditions like those of the present occurred about 5,000 years ago and stabilized the wide mixture of vegetation into organized recognizable plant communities. The upland zones consisted primarily of grassland communities and the riparian zones consisted primarily of woodland and aquatic communities.

Intrusion of weeds into grassland communities of the Northern Plains require open spaces in degraded ecosystems for the initial establishment. The rate of weed expansion within degraded communities progresses at different rates depending on the characteristics of the weeds intrinsic mechanisms to compete with degraded grass plants for sunlight, belowground nutrients, and soil water.

Noxious weeds (table 1) advance rapidly in degraded communities because they produce numerous seeds with long distance distributions, have high germination rates and remain viable for long periods, the mature plants develop long lived subterranean caudex that produce large quantities of dense aerial stems that shade the grass understory, and produce extensive aggressive lateral roots and rhizomes with high numbers of vegetative buds that are easily activated. All of these noxious weeds have recently been introduced, during the last couple of hundred years, into the Northern Plains grassland by human activity from other continents. Noxious weeds are the badest of the bad weeds and mandate obligatory prescribed treatments when and where ever they occur.

Aggressive weeds (table 2) advance quickly in degraded communities because they produce large quantities of seeds that can be transported long distances, that readily germinate producing large dense patches that shade the grass understory. The perennial plants produce subterranean crowns that produce aggressive roots and rhizomes with numerous vegetative buds. These aggressive weeds have recently been introduced, during the last couple of hundred years, into the Northern Plains grassland by human activity from other continents.

The prescribed treatments for the noxious and aggressive introduced weeds (tables 1 and 2) would include herbicides used as directed from this list: 2,4-D, dicamba (Banvil), picloram (Tordon), aminopyralid (Milestone), metsulfuron (Escort), imazapic (Plateau), triclopyr (Garlon), chlorsulfuron (Tela), and imazapyr (Arsenal) (Lym and Travnicek 2012). Reductions of weed quantities in degraded grasslands by prescribed treatments with herbicides does not correct the problems of the degraded grassland communities that continue to be susceptible to reinfestation by weeds.

The existence of woody species in grassland plant communities is not an ecological beneficial relationship. Woody species and grass plants are adversarial inhibitive competitors. Grasses and woody species compete for sunlight, mineral nitrogen, and soil water. The amount of woody trees and shrubs growing on the Northern Plains grasslands prior to European settlement is not known quantitatively but existence of woody species outside of the riparian zones appears to have been low. From the early aerial photographic record for parts of the Northern Plains, Smith (1988) reported that during the mid to late 1930's only about 5% of the upland grassland zones were occupied by woody species.

Woody species that have originated in other North American regional floras have encroached into Northern Plains grasslands primarily during the 160 years after the implementation of the Homestead Acts of the United States and Canada.

Large trees (table 3) reproduce by seed forming single stem plants usually long lived for 100's of years. Coniferous trees have no vegetative buds. Deciduous trees have vegetative buds on base of trunk, root crown, and lateral roots but have no rhizomes.

Small trees (table 3) reproduce by seed and vegetative buds forming multistem thickets of aerial stems usually short lived for 10's of years. The perennating belowground structures are usually long lived for 100's of years.

Coniferous shrubs (table 4) reproduce by seed forming numerous branches from a stem and have no vegetative buds.

Deciduous shrubs (table 4) form dense or loose clonal colonies with multiple aerial stems arising from numerous vegetative buds on extensive rhizome systems.

Subshrubs (table 5) have persistent perennial woody subterranean caudex or rhizome system with numerous vegetative buds which produce multiple annual herbaceous aerial stems that die back at the end of the growing season.

Succulent cactuses (table 5) have extensive shallow lateral root systems from which numerous jointed stems covered with barbed spines arise. Stem segments are readily detachable and transported, then develop roots and form new clumps.

The prescribed treatment for the woody trees (table 3), woody shrubs (table 4), woody subshrubs (table 5), and succulent cactuses (table 5) would include application of tebuthiuron pellets (Spike 2OP) at the rate of 0.5 lb ai tebuthiuron (2.5 lb product) per acre which is one pellet per square foot of land occupied by woody species (Manske 2006). One application of tebuthiuron recycles the active chemical through the plant and soil for 5 to 6 years with some decrease in quantity each cycle. Tebuthiuron is soil activated and absorbed by woody plants through the roots. The chemical interferes with or inhibits the photosynthetic processes, causing premature aging and shedding of the leaves. Production and shedding of successive sets of leaves cost the plant more nonstructural carbohydrates than the leaves produce during the brief period they are active. Several leaf defoliation cycles reduces stored nonstructural carbohydrates, when stored carbohydrates are completely depleted, both above- and belowground parts of the plant die. However, several woody species may have stored greater quantities of carbohydrates than can be reduced during the 5 or 6 year chemical active period for one application of tebuthiuron. A second application at half rate of 0.25 lb ai tebuthiuron (1.25 lb product) per acre would be necessary to deplete remaining nonstructural carbohydrates. Higher rates do not accelerate the carbohydrate depletion processes nor extend the length of the chemical active period. Rates greater than 0.75 lb ai tebuthiuron (3.75 lb product) per acre cause severe injury to perennial grasses (Manske 2006).

The grasslands of the Northern Plains have a low number of grass weeds. These grass weeds have been introduced into the Northern Plains from other continents.

Perennial grass weeds (table 6) produce numerous viable seeds, plants develop large mats with long branching rhizomes that have many vegetative buds that are easily activated. These grass weeds increase in native grasslands as a result of antagonistic traditional grazing practices.

Winter annual grass weeds (table 6) grow from seeds, produce very small quantities of forage during a short period before flower stalks develop. These grass weeds increase in native grasslands as a result of antagonistic traditional grazing practices and by winter grazing.

Poisonous grass weed (table 6) is an introduced bunch grass with short rhizomes being promoted as pasture forage with several companies providing seed for sale. All plants contain an endophytic fungus who's toxins can cause four nasty degenerative diseases in livestock (Manske 2018f).

The increased encroachment of woody shrubs and trees into grassland communities has been explained as a result of fire suppression (Humphrey 1962, Stoddart, Smith, and Box 1975, Wright and Bailey 1982). Fire cannot prevent the encroachment of or cause the removal of woody shrubs and trees in degraded grassland communities that can reproduce by vegetative buds (Wright and Bailey 1982, Manske 2019, 2020). The deciduous woody plants that have encroached into the Northern Plains grasslands can reproduce vegetatively (tables 3, 4, and 5), except big sagebrush has no vegetative buds (table 4). Coniferous trees (table 3) and coniferous shrubs (table 4) do not have vegetative buds and cannot reproduce vegetatively after a fire.

The increased intrusion of undesirable weedy forbs and introduced weedy grasses into grassland communities has also been explained as a result of fire suppression (Kirsch and Kruse 1972, Wright and Bailey 1982). Fire cannot prevent the intrusion of or cause the removal of weedy forbs and introduced grasses in degraded communities that produce large quantities of seeds and can produce vegetatively from subterranean caudex or rhizome systems with numerous vegetative buds. Noxious weeds (table 1), aggressive weeds, (table 2), and introduced grass weeds (table 6) cannot be extirpated by fire (Manske 2019, 2020).

Encroaching woody shrubs and trees and intruding weedy forbs and introduced weedy grasses can become established in degraded grassland communities only after the superior capability of grass plants to absorb nutrient resources and soil water has been degraded and reduced permitting the invading weeds to effectively compete for a portion of the belowground resources of nutrients and soil water (Peltzer and Kochy 2001, Manske 2020). Encroaching and intruding weeds cannot become established in healthy functioning grassland communities with grasses that have retained the superior capability of the nutrient resource uptake competitiveness mechanisms (Manske 2019, 2020).

Removal or reduction of introduced noxious and aggressive weeds, encroached woody trees and shrubs, and introduced weedy grasses by prescribed control treatments from degraded grassland ecosystems does not recuperate the problems of deteriorated grassland ecosystems. The open spaces that invited intrusion of the weeds still exist, retaining the grassland's susceptibility for reinfestation of undesirable weeds. This evidence strongly shows that the previous and current grassland management practices are not ecologically sound and necessitates change of the management practices. Northern Plains grasslands that require prescribed control treatments to reduce or remove undesirable weeds also require change of the grassland management practices.

There are two groups of indigenous forbs persisting on Northern Plains grasslands that are not weeds. The first group (table 7) cause medium to light belowground competition for grasses because the entire length of their root system is fully absorbent for mineral nutrients and soil water. The second group (table 8) cause little or no belowground competition for grasses because the top portion of their somewhat small root system has little or no absorption capacity, however, the deeper roots are fully absorbent.

Both of the groups of indigenous forbs (tables 7 and 8) are more passive opportunistic than aggressive, they produce low numbers of seeds that have low germination and short distance distribution, the annual aerial stems have low shading capability, and the taproot descends deep into the soil usually with short lateral roots that occupy little soil space. These indigenous forbs persist on Northern Plains grasslands because they are not in adversarial competition with healthy grass plants.

Healthy Northern Plains grasslands consist of indigenous grass plants and indigenous forbs that are not weeds. Maintenance of the competitive advantage of the grasses and retention of the indigenous forbs requires annual activation of the grass plant physiological growth mechanisms and the biogeochemical ecological processes that result from biologically effective management of partial defoliation by large grazing graminivores as described by Manske (2018a, e).

Acknowledgment

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Table 1. Noxious weeds that have intruded into Northern Plains grasslands.

Perennials

Leafy spurge, *Euphorbia esula* L., Eurasia
can form large infestations of dense clumbs, shades understory, has aggressive spreading rhizomes with numerous vegetative buds.

Canada thistle, *Cirsium arvense* L., Eurasia, North Africa
can form large dense colonies, shades understory, has aggressive extensive creeping rhizomes with vegetative buds.

Purple loosestrife, *Lythrum salicaria* L., Eurasia, Africa
can form dense monotypic stands in moist sites, shades understory, has large caudex with aggressive rhizomes.

Dalmatian toadflax, *Linaria dalmatica* L., Mediterranean
can form small patches, shades understory, has aggressive creeping rhizomes.

Yellow toadflax, *Linaria vulgaris* Mill., Eurasia
can form small patches, shades understory, has aggressive creeping rhizomes.

Russian knapweed, *Centaurea repens* L. Eurasia
can form large monoculture patches, shades understory, has aggressive spreading rhizomes.

Biennials

Spotted knapweed, *Centaurea micranthos* Lam., Eurasia
can form rapidly spreading patches, shades understory, produces numerous seeds that remain viable for more than 5 years.

Diffuse knapweed, *Centaurea diffusa* Lam., Eurasia
can form rapidly spreading patches, shades understory, produces numerous viable seeds that form winter rosettes.

Musk thistle, *Carduus nutans* L. Eurasia
can form large bunches, shades understory, produces numerous viable seeds that form winter rosettes.

Small tree

Saltcedar, *Tamarix* with 3 spp, Eurasia
can form large clumps with numerous stems and deep tap root, has root buds that can develop stems when top injured.

Subshrub

Absinth wormwood, *Artemisia absinthium* L., Eurasia
can form large clumps with numerous annual stems, has large long-lived woody caudex with short rhizomes.

Data from Lym and Travnicek 2012.

Table 2. Aggressive weeds that have intruded into Northern Plains grasslands.

Perennials

Common tansy, *Tanacetum vulgare* L., Europe
can form dense colonies, shades understory, has spreading rhizomes.

Field bindweed, *Convolvulus arvensis* L., Europe, western Asia
can form dense ground cover, has long intertwining stems that spread along ground and has extensive root system with vegetative buds.

Hoary cress, *Cardaria draba* (L) Desv., Middle East
can form dense monculture patches, shades understory, has aggressive rhizomes with numerous vegetative buds.

Perennial sowthistle, *Sonchus arvensis* L., Europe
can form small clusters, basal leaves can shade local understory, has extensive creeping rhizomes.

Biennials

Black henbane, *Hyoscyamus niger* L., Eurasia, North Africa
can form large plants from winter rosette, basal leaves shade understory, seeds viable for more than 5 years, can poison livestock.

Common burdock, *Arctium minus* (Hill) Beruh., Europe
can form large dense colonies, large leaves shade understory, has winter rosettes of large leaves, burs with numerous seeds entangle in animal fur.

Hounds tongue, *Cynoglossium officinale* L., Eurasia
can rarely form large patches, nutlets with numerous burs entangled in animal fur, seeds drop off and form winter rosette.

Annuals

Halogeton, *Halogeton glomeratus* (M. Bieb.) C. Meyor., Eurasia
can form spreading plants with several branches on open areas of bare saline-alkali soils, produces enormous quantities of seeds, plants can poison livestock.

Kochia, *Kochia scoparia* L., Eurasia
can form large spreading plants with several branches, produces thousands of seeds per plant.

Annual sowthistle, *Sonchus oleraceus* L., Europe
can form tall plants with multiple stems in highly disturbed areas.

Spiny sowthistle, *Sonchus asper* (L.) Hill, Europe
can form tall plants with multiple stems in highly disturbed areas.

Data from Lym and Travnicek 2012.

Table 3. Woody tree and small tree species that have encroached into Northern Plains grasslands.

Trees

Rocky Mountain juniper, *Juniper scopulorum* Sarg., Western Flora
can form small and medium size woodlands, shades understory, has taproot and shallow lateral roots, no vegetative buds, fire usually kills entire plant.

Ponderosa pine, *Pinus ponderosa* Lawson, Western Flora
can form small and medium size woodlands, shades undersory, has deep spreading roots, no vegetative buds, thick bark resists ground fire, crown fire kills most trees, pine needles can be poisonous to livestock.

American elm, *Ulmus americana* L., Eastern Flora
can form component of woodlands, shades understory, has vegetative buds on stem base and lateral roots.

Bur oak, *Quercus macrocarpa* Michx., Eastern Flora
can form groves and small woodlands, shades understory, has vegetative buds on root crown, base of trunk, and lateral roots.

Green ash, *Fraxinus pennsylvanica* March., Eastern Flora
can form small woodland in draws, shades understory, has vegetative buds on root crown and stem base.

Balsam popular, *Populus balsamifera* L., Northern Flora
can form dense colonies of single or multiple clones, shades understory, has vegetative buds on stem base, base of trunk, and lateral root.

Plains cottonwood, *Populus deltoides* Bartr., Eastern Flora
can form small groves with all trees of same age because seeds require three days of light rain to germinate, shades understory, has vegetative buds on root crown, base of trunk, and lateral roots.

Quaking aspen, *Populus tremuloides* Michx., Northern Flora
can form dense clonal grooves or bluffs that cover a few acres in size, shades understory, has vegetative buds on lateral roots.

Peachleaf willow. *Salix amygdaloides* Anders. Northern Flora
can form small thickets of multiple single stems, shades understory, has vegetative buds on root crown and base of trunk, and has no vegetative buds on roots.

Small trees

Beaked willow, *Salix bebbiana* Sarg., Northern Flora
can form multistem colonies, shades understory, has vegetative buds on root crown and stem base.

Juneberry, *Amelanchier alnifolia* Nutt. Northern and Western Flora
can form thickets of clustered stems, shades understory, has vegetative buds on root crowns, rhizomes, and stolons, can poison livestock.

Northern hawthorn, *Crataegus chrysocarpa* Ashe, Northern Flora
can form dense thickets of clustered stems, shades understory, has vegetative buds on stem base and lateral roots.

Wild plum, *Prunus americana* Marsh., Eastern Flora
can form dense thickets of multiple crooked stems, shades understory, has vegetative buds on root crown and lateral roots.

Pincherry, *Prunus pensylvanica* L., Northern Flora
can form clonal thickets, shades understory, has vegetative buds on stem base and lateral roots, can poison livestock.

Table 3 cont. Woody tree and small tree species that have encroached into Northern Plains grasslands.

Small trees
Chokecherry, *Prunus virginiana* L., Northern Flora can form extensive thickets of interconnected rhizomes, shades understory, has vegetative buds on root crown and rhizomes, can poison livestock.

Data from Manske 2019.

Table 4. Woody shrub species that have encroached into Northern Plains grasslands.

Shrubs

Common juniper, *Juniperus communis* L., Northern Flora
can form dense clumps with numerous branching stems, shades understory, root crown has no vegetative buds, contains highly flammable resinous foliage and fire usually consumes entire plant.

Creeping juniper, *Juniperus horizontalis* Moench. Northern Flora
can form mats with numerous prostrate creeping stems, shades understory, has tree size taproot and no vegetative buds, contains highly combustible resinous foliage and fire usually consumes entire plant.

Coyote willow, *Salix exigua* Nutt., Western Flora
can form large clonal colonies with network of lateral roots, has vegetative buds on root crown, stem base, and lateral roots.

Sandbar willow, *Salix interior* Rowlee. Northern Flora
can form large dense thickets with network of aggressive rhizomes, has vegetative buds on rhizomes.

Prairie willow, *Salix humilis* Marsh., Eastern Flora
can form clonal colonies, has vegetative buds on root crowns and stem base.

American hazelnut, *Corylus americana* Walt., Northern and Eastern Flora
can form dense colonial thickets with extensive network of rhizomes, has vegetative buds on root crown and rhizomes.

Beaked hazelnut, *Corylus cornuta* Marsh., Northern and Eastern Flora
can form dense colonial thickets with extensive network of rhizomes, has vegetative buds on root crown and rhizomes.

Kinnikinnick, *Arctostaphylos uva-ursi* (L.) Spreng., Northern Flora
can form dense mats with prostrate creeping stolons and numerous upward stems, has vegetative buds on root crowns, stem base, trunk base, and stolons.

Shubby cinquefoil, *Dasiphora floribunda* (Pur.) Kart. Northern Flora
can form mat with numerous erect branching stems, has vegetative buds on the root crown, fibrous bark is extremely flammable causing high intensity flash burns.

Sand Cherry, *Prunus pumila* L., Eastern Flora
can form clonal colonies with network of abundant rhizomes and extensive spreading lateral roots, has vegetative buds on root crown, rhizomes, and lateral roots, can poison livestock.

Prickly wild rose, *Rosa acicularis* Lindl., Northern Flora
can form colonies of stout stems linked by widespread rhizomes system, has vegetative buds on rhizomes.

Prairie wild rose, *Rosa arkansana* Porter, Western Flora
can form small clumps of annually regrown stems from long lived caudex, has vegetative buds on root crown and lateral roots.

Smooth wild rose, *Rosa blanda* Ait., Eastern Flora
can form clonal colonies of numerous woody stems with no prickles arising from woody caudex, has vegetative buds on root crown and lateral roots.

Western wild rose, *Rosa woodsii* Lindl. Western Flora
can form dense nearly impenetrable thickets consisting of numerous multiple stem bases interconnected with shallow rhizome system, has vegetative buds on the root crown and rhizomes.

White spiraea, *Spiraea alba* Du Roi, Eastern Flora
can form clonal colonies from rhizome system, has vegetative buds on root crown and rhizomes.

Table 4 cont. Woody shrub species that have encroached into Northern Plains grasslands.

Shrubs

Leadplant, *Amorpha canescens* Pursh. Eastern Flora
can form clonal colonies consisting of numerous multiple stemmed root crowns interconnected by rhizome system, has vegetative buds on root crown and rhizomes, has symbiotic rhizobia bacteria in nodules on roots.

False indigo, *Amorpha fruticosa* L., Eastern Flora
can form sizeable clonal colonies of numerous stem bases with clustered stems interconnected by extensive spreading lateral roots, has vegetative buds on root crown and lateral roots, has symbiotic rhizobia bacteria in nodules on roots.

Dwarf wild indigo, *Amorpha nana* Nutt., Eastern Flora
can form open cluster of stems interconnected by rhizome system, has vegetative buds on root crown, rhizomes, and lateral roots.

Silverberry, *Elaeagnus commutata* Bernh., Northern Flora
can form extensive loose clonal colonies of numerous stem bases with single aerial stem interconnected by complex branched rhizome system, has vegetative buds on stem base, rhizomes, and stolons, has symbiotic rhizobia bacteria in nodules on roots.

Buffaloberry, *Shepherdia argentea* (Pursh) Nutt., Western Flora
can form tall dense impenetrable unisexual clonal thickets with stem base interconnected by extensive rhizomes system, has vegetative buds on root crown and rhizomes, has symbiotic rhizobia bacteria in nodules on branched roots.

Fragrant sumac, *Rhus aromatica* Ait., Eastern Flora
can form clonal thickets consisting of numerous stem bases with multiple branching stems interconnected by extensive rhizome system, shades understory, has vegetative buds on root crowns, rhizomes, and lateral roots.

Skunkbush, *Rhus trilobata* Nutt., Western Flora
can form patches of clonal thickets consisting of numerous stem bases with multiple irregular spreading branching stems interconnected by spreading woody rhizome system, shades understory, has vegetative buds on root crown and rhizomes.

Western snowberry, *Symphoricarpos occidentalis* Hook., Northern Flora
can form large dense low colonies consisting of numerous stem bases with multiple stems that add new set of branches each growing season, stem bases are interconnected by aggressive rhizome system, shades understory, has vegetative bud pairs on stem base and rhizomes at about 1 inch increments.

Fourwing saltbush, *Atriplex canescens* (Pursh) Nutt., Great Basin Flora
can form tall clump of branching stems that have spines arising from large stem base, shade understory, has vegetative buds on root crown, base of trunk, stem base, and rhizomes (if present).

Greasewood, *Sarcobatus vermiculatus* (Hook.) Torr. Great Basin Flora
can form large tall clonal clumps of multiple branching stems arising from large root crown, shades understory, has vegetative buds on root crown and lateral roots, can poison livestock.

Sand sagebrush, *Artemisia filifolia* Torr., Western Flora
can form patches of single stem plants with numerous irregular branches arising from woody stem base, shades understory, has vegetative buds on stem base.

Plains silver sagebrush, *Artemisia cana* Pursh., Western Flora
can form large clonal colonies of numerous stem bases with several twisted stems that have numerous irregular branches interconnected by aggressive rhizome network, shades understory, has vegetative buds on stem base, rhizomes, and lateral roots, seeds have high germination rate.

Table 4 cont. Woody shrub species that have encroached into Northern Plains grasslands.

Shrubs

Wyoming big sagebrush, *Artemisia tridentata* Nutt., Western Flora

can form extensive patches of long-lived plants with several twisted stems that have numerous stout branches arising from stem base, shades understory, has no vegetative buds, fire and mechanical damage can completely kill plants, seedlings can be established only in areas devoid of grass cover.

Rubber rabbitbrush, *Ericameria nauseosa* Nesom & Baird, Great Basin Flora

can form a large rounded crown of numerous annual die back aerial stems produced from a short stout woody trunk that arises from a stem base, shades understory, has vegetative buds on trunk and root crowns.

Yellow rabbitbrush, *Chrysothamnus viscidiflorus,* (Hook.) Nutt., Great Basin Flora

can form compact crowns of annual die back aerial flower stalks growing on several spreading woody stems arising from a stem base, shades understory, has vegetative buds on trunk and stem base.

Great Plains yucca, *Yucca glauca* Nutt., Western Flora

can form loose colonies of numerous short stout woody stems with spirally arranged rosettes of stiff, bayonet shaped, sharptipped leaves; the woody stems arise from a stem base that has an extensive network of rhizomes that interconnect numerous stem bases, has vegetative buds on stem base and rhizomes.

Data from Manske 2016, 2019.

Table 5. Woody subshrub and succulent species that have encroached into Northern Plains grasslands.

Subshrubs

Wild licorice, *Glycyrrhiza lepidota* Pursh., Western Flora

can form large clonal colonies of annual die back erect stems arising from deep extensive woody rhizome system with many long branches, fruit pods covered with burlike hooked prickles that tangle with animal fur, has vegetative buds on rhizomes.

Moundscale saltsage, *Atriplex gardneri* (Moq.) Dietr., Western Flora

can form large dense spreading tufts of many herbaceous stems arising from a decumbent woody stem base, has vegetative buds on root crown, stem base, and lateral roots, has low flammability resulting in a high tolerance of fire.

Winterfat, *Krascheninnikovia lanata* Meeuse & Smit, Western Flora

can form stem clumps of numerous erect annual secondary herbaceous stems arising from a long lived central woody stem base that develops from a woody root crown, has numerous perennating buds on the central woody stem base and vegetative buds on the root crown.

Green sage, *Artemisia dracunculus* L., Western Flora

can form patches of multiple stem clumps arising from thick horizontal rhizomes, stems are unbranched until tip removed by browsing, has vegetative buds on rhizomes, has symbiotic mycorrhiza fungi develop on roots.

Fringed sage, *Artemisia frigida* Willd., Western Flora

can form dense mats of clumps with solitary to numerous (after tip browsed) herbaceous annual flower stems arising from tough woody crown base interconnected by rhizome network, has vegetative buds on stem base and rhizomes, has symbiotic mycorrhiza fungi develop on roots.

White sage, *Artemisia ludoviciana* Nutt., Western Flora

can form large loose to dense colonies of numerous stem bases that produce solitary to several herbaceous stalks that die back during winter interconnected by a dense network of coarse woody aggressive rhizomes, has vegetative buds on stem base and rhizomes.

Broom snakeweed, *Gutierrezia sarothrae* Britt. & Rusby, Western Flora

can form dense stem clusters of numerous die back annual flower stalks that develop from a single to several woody spreading ground level decumbent short lived stems arising from a stem base, has vegetative buds on woody trunk and root crown, can poison livestock.

Succulent cactuses

Fragile prickly pear, *Opuntia fragilis* (Nutt.) Haw., Southwestern Flora

can form low growing inconspicuous clumps of numerous bilaterally flattened jointed stems with easily detached segments covered with barbed spines arising from an extensive shallow lateral root system, detached stem segments develop roots forming new clumps.

Plains prickly pear, *Opuntia polyacantha* Haw., Western Flora

can form large low clumps of numerous strongly flattened jointed stem pads with detachable segments covered with two types of barbed spines arising from an extensive shallow lateral root system, detached pads develop roots forming new clumps.

Data from Manske 2016, 2019.

Table 6. Grass weeds that have intruded into Northern Plains grasslands.

Kentucky bluegrass, *Poa pratensis* L. Europe

can form thick mats with long dense creeping rhizome system, has shallow fine root system, is high water user and a high nitrogen user causing reduced forage biomass production and a long summer dormancy period, has numerous vegetative buds on crowns and rhizomes weakly inhibited and easily activated producing large quantities of tillers.

Canada bluegrass, *Poa compressa* L., Europe

can form loose open mats with long intervals between nodes of numerous tillers on frequently branching aggressive rhizome system, has fine fibrous branching roots that descend deep into the soil, is a high water user, vegetative buds are weakly inhibited and easily activated.

Smooth bromegrass, *Bromus inermis* Leyss., North and South Europe

can be beneficial and pestiferous because of high seed viability, strong seedling vigor, and long stand longevity that permits escape and invasion into numerous environments with degraded vegetation, grows best with 18 or greater inches of rain per year, has two strains; rare Northern Type produces mostly crown tillers forming tussocks (bunches) and common Southern Type produces mostly rhizome tillers forming loose mats.

Japanese brome, *Bromus japonicus* Thumb., Eurasia

undesirable cool-season annual weed, grows from seed as winter annual or very early spring, has shallow fibrous roots, develops basal rosette of leaves with several flower stalks, flowers early spring, dry plants highly flammable, increases in degraded grassland ecosystems.

Downy brome (Cheatgrass), *Bromus tectorum* L., Mediterranean

undesirable cool-season annual weed, grows from seed as winter annual or very early spring, seeds germinate only from 1 inch or less soil depths, seeds viable for four years, develops tuffed plants with several flower stalks from one root crown, flowers early spring, stiff awns troublesome to livestock, dry plants are fire hazard, has low competitiveness against healthy perennial grasses, increases under winter grazing and heavy growing season grazing.

Tall fescue, *Schedonorus arundinaceus* Dumort. Europe

can form large bunches of numerous crown tillers and several tillers from short rhizomes, has extensive coarse roots that can descend deep into soil, has mid summer dormancy period, all plants contain endophytic fungus that produce toxins that poison livestock resulting in four unusual syndromes that severely reduce productivity and cause the inability to maintain pregnancy.

Data from Manske 2018b.

Table 7. Persistent nonweedy indigenous forbs that cause medium to light nutrient uptake competition for grasses on the Northern Plains grasslands.

Perennials

Prairie spiderwort, *Tradescantia occidentalis* (Britton) Smyth.
can form dense colonies with single annual stems arising from a subterranean crown, shallow thick white fleshy root tufts are fully absorbent along entire length, this monocot that is somewhat tolerant of shade can persist through harsh conditions on healthy Northern Plains grasslands.

Prairie chickweed, *Cerastium arvense* L.
can form wide dense mats with numerous trailing, prostrate, stems with spreading lateral branches arising from long creeping rhizomes, a main taproot with numerous fibrous lateral roots are absorbent, this dicot can persist through harsh conditions on healthy Northern Plains grasslands.

Prairie cinquefoil, *Potentilla pensylvanica* L.
can form as individual plants that start as a basal rosette that produces one to several stems arising from a perennating branched crown (caudex), a single taproot has numerous fibrous lateral roots that are absorbent, this dicot herb can persist through harsh conditions on healthy Northern Plains grasslands.

Purple locoweed, *Oxytropis lambertii* Pursh.,
can form as individual plants that start as a tufted rosette of basal leaves and a leafless flower stalk, no stems (acaulescent) arising from a stout knobby crown (caudex), a main stout taproot has a few main roots with no branches are fully absorbent throughout the entire length, can poison livestock, this legume is commonly present at low abundance on healthy Northern Plains grasslands.

Toothleaved evening primrose, *Calylophus serrulatus* (Nutt.) Raven.
can form small loose colonies of multiple annual woody stems arising from a persistent stout woody crown (caudex) interconnected by a creeping horizontal rhizome system, a long, tough taproot and numerous horizontally spreading roots descend vertically have the capacity for vigorous absorption of water and nutrients throughout the entire length, this dicot primrose can persist through harsh conditions on healthy Northern Plains grasslands.

Narrowleaved puccoon, *Lithospermum incisum* Lehm.
can form as individual plants with one to several annual branched stems arising from a persistent woody crown (caudex), a stout woody taproot with short unbranched lateral roots along entire length are fully absorbent throughout the entire depth, this dicot borage can persist through harsh conditions on healthy Northern Plains grasslands.

Western Yarrow, *Achillea millefolium* L.
can form small dense colonies with a rosette of basal leaves followed by a loose cluster of annual stems arising from an enlarged crown formed at end of a short rhizome, a short taproot and short fibrous roots develop from each crown, this dicot herb is commonly present but as a minor component on healthy Northern Plains grasslands.

Field pussytoes, *Antennaria neglecta* Greene,
can form small dense mats with rosettes of basal leaves arising from enlarged root crowns at nodes on long, ground hugging stolons along with dioecious inflorescence developed atop leafless hairy scapes, numerous main roots with fibrous lateral roots develop at each crown and are highly absorbent at all depths, this dicot herb can persist through harsh conditions on healthy Northern Plains grasslands.

Small leaf pussytoes, *Antennaria parvifolia* Nutt.,
can form small dense mats of alternate basal leaves arising from enlarged root crowns (caudex) at nodes on extensive stolons along with dioecious inflorescence developed on a flower stalk, numerous vertical and horizontal fibrous roots develop at each crown and are absorbent at all depths, this dicot herb is commonly present but as a minor component of healthy Northern Plains grasslands.

Table 7 cont. Persistent nonweedy indigenous forbs that cause medium to light nutrient uptake competition for grasses on the Northern Plains grasslands.

Perennials

Wavyleaf thistle, *Cirsium undulatum (Nutt.)* Spreng.,

can form small patches from annual offset sprouts developed from adventitious root buds on a perennating subterranian crown (caudex), a stout thick, deep, subterranean taproot with several horizontal runner roots develop from the crown, this short lived thistle can persist through harsh conditions on Northern Plains grasslands.

Stiff sunflower, *Helianthus rigidus* (Cass.) Desf.

can form small patches or open colonies with several single annual stiff stems developing from rhizome nodes extending outward from an enlarged perennating subterranean crown, several large tough woody roots spread radially from the crown and numerous short fibrous roots that are highly branched descend from woody roots with a dense concentration in top 12 inches of soil and have a capacity for great absorption, this dicot sunflower can persist through harsh conditions on Northern Plains grasslands.

Blue wild lettuce, *Lactuca oblongifolia* Nutt.,

can form small patches with several single annual branched stems developing from rhizome nodes extending outward from an enlarged perennating subterranean crown, has a deep taproot with extensive white absorbent lateral roots, this mid succession dicot herb is commonly present at low to moderate abundance on healthy Northern Plains grasslands.

Early goldenrod, *Solidago missouriensis* Nutt.,

can form large open patches to dense colonies with several single or groups of unbranched smooth reddish stems arising from rhizome nodes that extend outward from an enlarged woody perennating subterranean crown (caudex), a few large white cord-like main roots spread radially to 20 inches then descend to depths of 7 feet and clusters of short and branched fine roots concentrate in top 2 feet of soil with roots at all depths vigorous absorbers, this short-lived dicot goldenrod is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Soft goldenrod, *Solidago mollis* Bartlett,

can form large open colonies with several single or loose clusters of annual stems arising from nodes on extensive creeping rhizomes extending outward from an enlarged perennating subterranean crown, numerous roots arising from crown spread horizontally then descend to 8 feet and numerous lateral roots from the main roots have greatest development in top 2 feet of soil and all roots have capacity for vigorous absorption, this dicot goldenrod is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Stiff goldenrod, *Solidago rigida* L.

can form open patches with several groups of stiff, stout unbranched stems arising from nodes on a thick, stout, branched woody, rhizome system developed from a stout subterranean crown, numerous main roots spread horizontally for 18 inches from crown then descend to 6 foot depth and numerous fine unbranched lateral roots from the main roots fill the soil to 2 feet depth and all roots have capacity for vigorous absorption, this dicot goldenrod is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Biennials

Slim rockcress, *Arabis holboellii* Hornem.,

can form as individual plants with first year growth consisting of a small basal rosette and second year growth consisting of a single simple stem, damage to aerial parts prior to senescence activates regrowth shoots from the crown, a taproot with numerous fibrous lateral roots occupies a small area of soil, this biennial mustard is commonly present at low to moderate abundance and can persist through harsh conditions on Northern Plains grasslands.

Table 7 cont. Persistent nonweedy indigenous forbs that cause medium to light nutrient uptake competition for grasses on the Northern Plains grasslands.

Biennials

Western wallflower, *Erysimum asperum* (Nutt.) DC.

can form as individual plants with first year growth consisting of a basal rosette and second year growth consisting of a single widely branched above stiff stem, damaged aerial parts prior to senescence activates regrowth shoots from crown, a taproot with numerous fibrous lateral roots occupies a small area of soil, this biennial mustard is commonly present at low abundance and can persist through harsh conditions on Northern Plains grasslands.

Daisy fleabane, *Erigeron strigosus* Muhl. ex Willd.

can form as individual plants with first year growth consisting of a basal rosette and second year growth consisting of a few simple stems, damage to aerial parts activates limited regrowth shoots from the existing crown, a shallow branching taproot has extensive spreading secondary fibrous roots occupies a small area of soil, this short lived dicot is usually present at low abundance and can persist on Northern Plains grasslands.

Curly cup gumweed, *Grindelia squarrosa* (Parsh) Dunal,

can form as individual plants with first year growth consisting of a rosette of basal leaves and second year growth consisting of solitary whitish stem much branched above, damage to aerial parts prior to senescence activates regrowth from short rhizomes developed from the crown, a taproot descends down to 6 feet deep has abundant lateral roots that spread radially to 2.3 feet with all roots having capacity for vigorous absorption, this short lived early succession forb is present on degraded areas of Northern Plains grasslands.

Annuals

Peppergrass, *Lepidium densiflorum* Schrader,

can form as individual plants with early growth consisting of a winter basal rosette and spring growth as a solitary stem widely branched above, damage to aerial parts prior to senescence activates regrowth shoots from crown, a taproot with numerous fibrous lateral roots occupies a small area of soil, this dicot mustard is usually present at low densities for less than half of the growing season on healthy Northern Plains grasslands.

Prairie trefoil, *Lotus purshianus* Clem. & Clem.

can form as individual plants during years with good spring rain with a single much branched stem, a slender taproot has fine lateral roots occupies a small area of soil, this mid succession legume grows from seed and is commonly present during growing seasons with good early spring precipitation on Northern Plains grasslands.

Rough pennyroyal, *Hedeoma hispida* Pursh,

can form as individual plants from a seed followed by rapid development of growth stages during growing seasons that receive 16% to 36% greater early season precipitation than the long-term mean, a shallow main root with short lateral roots descends to 2 inches deep and occupies a very small area of soil, this small inconspicuous mint is intermittently present on Northern Plains grasslands.

Wooly plantain, *Plantago patagonica* Jacq.,

can form as individual plants from a seed with late summer or fall basal rosette and spring growth consisting of a set of basal leaves and an inflorescence on a leafless scape, a short taproot has fine fibrous lateral roots, this small dicot contributes little and uses little and is present when fall months or early spring months receive above average precipitation.

Table 7 cont. Persistent nonweedy indigenous forbs that cause medium to light nutrient uptake competition for grasses on the Northern Plains grasslands.

Annuals
Horseweed, *Conyza canadensis* (L.) Crong., can form as individual plants from seed with late summer or fall rosette and during spring a single stiff stem, a taproot with numerous fine lateral roots develops from the crown, damage to aerial parts prior to senescence activates regrowth from the crown, this early succession annual forb is usually present at low abundance on Northern Plains grasslands.

Data from Manske 2017.

Table 8. Persistent nonweedy indigenous forbs that cause little or no nutrient uptake competition for grasses on the Northern Plains grasslands.

Perennials

White wild onion, *Allium textile* Nelson & Macbride

can form as an individual plant with two equal annual basal leaves arising from a whorl atop an egg shaped bulb, numerous short tufted roots arise from the base of the bulb, damage to aerial leaves and leafless scape activates regrowth shoots from the top of the bulb, this late succession monocot is present at low abundance on healthy Northern Plains grasslands.

Scarlet globemallow, *Sphaeralcea coccinea* (Nutt.) Rydb.

can form as a small clump as several clustered stems arise from a long-lived persistent subterranean woody crown, a main stout woody taproot develops from the crown and descends to 35 inches unbranched and then divides and descends to 13 feet, additional long thin lateral roots arise from the top of the taproot and descends parallel to the taproot, small horizontal roots extend 8 inches from the taproot, absorption of roots in the top 2 feet of soil is not important, absorption of roots in the lower depths is of great importance, this late succession dicot is present at usually low abundance and can persist through harsh conditions on Northern Plains grasslands.

Groundplum, *Astragalus crassicarpus* Nutt.,

can form a large dense clump with numerous annual coarse, fleshy, decumbent stems arise from a large subterranean crown (caudex), a stout taproot descends from the crown to 12 feet and several main roots arise from the taproot spread horizontally to 1.5 feet then the many branches descend to 6 feet with numerous fibrous lateral roots, all roots in top 12 inches of soil have little or no absorption capability while all roots below are absorbent, this late succession legume is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Missouri milkvetch, *Astragalus missouriensis* Nutt.,

can form small clumps with several short, tufted, annual stems arising from branched crown (caudex), a stout prominent taproot has numerous fibrous lateral roots, top 1 foot of all roots have low or no absorption capacity, and roots below are highly absorbent, vegetative buds are on crown branches, this dicot legume is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Purple prairie clover, *Dalea purpurea* Vent.,

can form small clumps with several erect annual stems arising from a subterranean woody crown (caudex), a coarse nonfibrous woody taproot can descend to 8 feet and several orange-brown lateral roots extend horizontally 18 inches then descend to 4.5 feet, all roots have little or no absorption in top 12 inches of soil, survival is highly dependent on mycorrhizal fungi for uptake and transport of soil nutrients, vegetative buds are on crown and crown branches, this dicot legume is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Silverleaf scurfpea, *Psoralea argophylla* Pursh,

can form as individual plant with a single annual stem arising from a subterranean branched crown (caudex), a main woody taproot tapers rapidly and descends to 5.5 feet and has several short unbranched fine lateral roots along entire length, all roots have little or no absorption in top 6 inches of soil, vegetative buds are on crown and crown branches, this dicot legume is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Indian breadroot,*Psoralea esculenta* Pursh,

can form as individual plant with single erect annual stem with spreading branches arising from a thickened vertical crown (caudex), a prominent taproot descends straight downward and develops a large egg shaped storage organ at about 4 inches depth and develops fibrous lateral roots below, all roots above storage organ are not absorbent, vegetative buds are on the vertical crown, this dicot legume is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Table 8 cont. Persistent nonweedy indigenous forbs that cause little or no nutrient uptake competition for grasses on the Northern Plains grasslands.

Perennials

American wildvetch, *Vicia americana* Muhl. ex Willd.,
can form dense but limited colonies with a single, annual, long, branched climbing vines arising from a few to several perennating subterranean crown (caudex) interconnected by short rhizomes, a moderate to deeply branched taproot descends to 40 inches from each crown, all roots, in top 2 inches of soil have little or no absorption, vegetative buds are on the crowns and rhizomes, this dicot legume is usually present at low abundance and can persist through harsh conditions on Northern Plains grasslands.

Scarlet gaura, *Gaura coccinea* Nutt. ex Pursh,
can form large colonies with a single to several annual branched stems arising from few to several persistent subterranean woody crowns (caudex) interconnected by an extensive spreading horizontal rhizome system, a deep, thick taproot with fibrous lateral roots descends from each crown, vegetative buds are on the crowns and rhizomes, this dicot primrose is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Whorled milkweed, *Asclepias verticillata* L.
can form a short string of individual annual unbranched stems spaced a few inches apart arising from a few to several persistent fibrous root crowns interconnected by short rhizomes, deep fibrous roots compressed into bundles descend from each crown, this root system has only a minor effect upon grass plants, vegetative buds are on crowns and rhizome nodes, this long lived milkweed should be present and can persist through harsh conditions on Northern Plains grasslands.

Hood's phlox, *Phlox hoodii* Richardson,
can form small moss like mats with numerous annual branching stems in compact dense tufts arise from a persistent woody root crown (caudex), a main coarse woody taproot with short lateral roots descends to 37 inches from crown, all roots in top 4 inches of soil have little or no absorption, vegetative buds are on the crown, this small dicot is commonly present and persistent through the conditions on Northern Plains grasslands.

White beard tongue, *Penstemon albidus* Nutt.,
can form as individual plant with single to few stocky annual stems arising from a persistent, short caudex, a taproot with fibrous lateral roots descends from crown and has only a minor effect upon grass plants, vegetative buds are on the crown and crown branches, this dicot figwort is commonly present and can persist through harsh conditions on Northern Plains grasslands.

White prairie aster, *Aster ericoides* L.,
can form clumps of stem clusters with numerous annual stems in a bushy crown arising from thick stem bases interconnected by short, slender, woody, rhizomes, thin fibrous roots descend vertically from crowns to 8 foot depths, roots have only a minor effect upon grass plants, vegetative buds are on stem bases and rhizomes, this dicot aster is commonly present as a minor component at low densities on Northern Plains grasslands.

Smooth blue aster, *Aster laevis* L.,
can form clumps of stem clusters with few stout, annual stems widely bunched above arise from a persistent thick stout crown (caudex), extensive fibrous roots descend vertically from the crown, roots have only a minor effect upon grass plants, vegetative buds are on the crown and the short branch rhizomes, this dicot aster is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Table 8 cont. Persistent nonweedy indigenous forbs that cause little or no nutrient uptake competition for grasses on the Northern Plains grasslands.

Perennials

Purple coneflower, *Echinacea angustifolia* DC.,
can form as individual plants with a rosette of basal petioled leaves and one to a few stiff, annual stems arising from a perennating crown (caudex), a thick black, woody taproot descends vertically from the crown to 6.5 feet deep with branches forming at lower depths, roots have only a minor effect upon grass plants, vegetative buds are on the crown and taproot, this late succession forb is commonly present on Northern Plains grasslands.

Spiny ironweed, *Haplopappus spinulosus* (Pursh) DC.,
can form small clump of stems with numerous, erect, annual stems widely branched above arise from a woody, branching crown (caudex), a strong woody taproot with numerous fibrous lateral roots extending radially to 1.5 feet descend from crown to 5.0 foot depth, roots have little or no absorption in top 1 foot of soil and have good absorption at lower depths, vegetative buds are on crown and crown branches, this late succession forb is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Hairy goldenaster, *Heterotheca villosa* (Pursh) Shinners,
can form clump with numerous simple annual stems arising from a perennating woody crown (caudex), a main woody taproot descends to 3 feet from crown divides into branches and descends to 13 feet, two or three primary roots develop from taproot at about 2.5 foot depth, spread horizontally for 2 feet then descends to depth of taproot and have few to no lateral roots, all roots have little or no absorption in top 3 feet of soil, and provide much absorption capacity at lower depths, vegetative buds are on the crown and short rhizome branches, this aster is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Narrowleaved blazing star, *Liatris punctata* Hook.,
can form as individual plant with single to few stiff, annual unbranched stems arising from a thick, solid, subterranean, woody, rootstock that develop annual rings as mature, a large fleshy carrot-shaped taproot descends to 12 inches then branches and descends to 7 or 16 feet and numerous fine fibrous lateral roots extend radially to 3.5 feet then fine branches descend to 10 feet, all roots in top 3 feet of soil have little or no absorption, vegetative buds are on woody rootstock and short rhizomes, this long-lived late succession aster is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Skeletonweed, *Lygodesmia juncea* (Pursh) D. Don ex Hooker,
can form as individual plant with single, annual, stiff, stem arising from perennating crown, a single thin taproot with tiny lateral roots less than 1 inch long descends to 18 feet, roots have only a minor effect upon grass plants, vegetative buds are on crown and rhizomes, this dicot herb is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Longheaded coneflower, *Ratibida columnifera* (Nutt.) Woot. & Standl.,
can form as individual plant with single to few branched above annual stems arising from a perennating woody crown (caudex), a stout prominent taproot descends to 3.5 feet, numerous fibrous lateral roots extend radially to 12 inches then form branches that descend to 3.5 feet, all roots in top 12 inches of soil have little to no absorption and provide much absorption capacity at lower depths, vegetative buds are on the crown, this late succession forb is commonly present and can persist through harsh conditions on Northern Plains grasslands.

Data from Manske 2017.

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Attaining Full Functionality of Grassland Ecosystems with the Twice-over Rotation Grazing Management Strategy

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Functionality of grassland ecosystems at full biological potential requires recycling adequate quantities of essential elements through the biogeochemical processes performed by the belowground soil microbes in order to replace removed aboveground leaf and stem biomass of grass plants through the primary physiological growth mechanisms, all of which must be activated annually by partial defoliation by grazing graminivores during vegetative growth stages of grass lead tillers.

Grasslands of the Northern Plains managed by traditional practices are low in available mineral nitrogen. This low nitrogen availability has long been known to be responsible for the reduced herbage productivity and below genetic potential calf weight gains per acre. However, intact grasslands have adequate nitrogen, usually at 5 to 6 tons of organic nitrogen per acre, which is not available to plants. Organic nitrogen must be mineralized by soil microorganisms in order for it to be available for plant use in the inorganic form. Unfortunately, traditional and gimmick grazing management practices do not elevate the soil microorganism biomass high enough to support mineralization of organic nitrogen at a level that can yield a supply at the threshold quantity of 100 lbs/ac or greater (Wight and Black 1972, 1979), which will permit the four primary grass plant growth mechanisms and all of the ecosystem biogeochemical processes to function at potential biological levels.

Intact grassland ecosystems that are low in available mineral nitrogen cannot be improved with some quick fix agronomic practice. The application of nitrogen fertilizer to grassland ecosystems does not solve the complex problems related to the cause of low soil mineral nitrogen (Manske 2014). It was found that nitrogen fertilization of native grasslands caused a synchronization of grass tiller growth stage development, resulting in a small increase in herbage biomass which later produced a high rate of leaf senescence and an early season decrease in forage nutritional quality compared to nonfertilized grasslands (Manske 2014). It also caused a short term shift in plant species composition, with an increase in mid cool season grass (e.g. western wheatgrass) and a decrease in short warm season grasses (e.g. blue grama) (Manske 2009a, 2014). Initially, these changes were considered by most observers to be beneficial (Manske 2009d). However, close examination of the data showed that the costs of the additional herbage weight were excessive (Manske 2009b), and that the long term disruptions of ecosystem biogeochemical processes were detrimental to desirable plant composition (Manske 2010). The reduction of short warm season grasses caused a decrease in total live plant basal cover, thus exposing greater amounts of soil to higher levels of solar radiation and erosion (Goetz et al. 1978). These large areas of open space became ideal invasion sites for undesirable plants, resulting in a long term plant species compositional shift towards a replacement community of domesticated and introduced mid cool season grasses (e.g. Kentucky bluegrass, Smooth bromegrass), and in the removal of nearly all the native plant species (Manske 2009c, 2010, 2018a).

Implementation of the strategy to interseed alfalfa into intact semiarid native grassland does not solve the complex problems related to the cause of low soil mineral nitrogen (Manske 2005). The introduction of alfalfa increased demand on the existing low levels of soil mineral nitrogen because almost all of the alfalfa plants' nitrogen requirements had to be taken from the soil. The interseeded alfalfa plants had extremely low levels of nodulation of rhizobium bacteria on the roots and, consequently, almost no nitrogen fixation. The inoculated rhizobium had been consumed by the resident soil microbes before the alfalfa seedlings had grown sufficient root material to permit infection (Manske 2004). The low amounts of mineral nitrogen available in the soil resulted in slower rates of growth and higher rates of mortality for the interseeded alfalfa plants than those for alfalfa plants solid seeded into cropland (Manske 2005). In addition, the high water use of the interseeded alfalfa plants depleted soil water levels within a 5 foot radius from each crown to an average of 35% below ambient soil water levels, causing drought stress conditions in the adjacent grass plants and, subsequently, further reducing grass herbage production (Manske 2004, 2005). Agronomic strategies implemented on grassland ecosystems slowly stifled grass internal growth mechanisms and ecosystem biogeochemical processes to ineffectiveness (Manske 2018a).

Grassland ecosystems should be managed with sound ecological principles. The ecological method to increase the quantity of available mineral nitrogen to 100 lbs/ac or greater in grassland ecosystems is to increase the biomass of the rhizosphere microorganisms. The rhizosphere is the narrow zone of soil bonded by extracellular adhesive polysaccharides around active roots of perennial grassland plants. The primary biologically active rhizosphere microbes are the endomycorrhizal fungi, ectomycorrhizal fungi, low carbon: high nitrogen bacteria, and normal carbon: nitrogen protozoa. The rhizosphere microbes do not possess chlorophyll nor do they have direct access to sunlight, as a consequence, these microbes are deficient of energy and require an outside source of simple carbon energy. Contrary to common assumptions, there isn't enough short chain carbon energy in recently dead grass material and there isn't enough energy from natural plant leakage to support a large active biomass of soil microbes. The only readily accessible source of large quantities of short chain carbon energy is the surplus fixed carbon energy photosynthesized by grass lead tillers at vegetative phenological growth stages. Grass plants fix a great deal more carbon energy than they use, furthermore, grass plants do not store the surplus fixed energy until during the winter hardening period, which starts in mid August and lasts to hard frost. Surplus carbon energy not programed for use, is broken down during night respiration. However, grass lead tillers at vegetative growth stages, between the three and a half new leaf stage and the flower (anthesis) stage, can be manipulated to exudate most of the surplus carbon energy into the rhizosphere through the roots following partial removal of 25% to 33% of the aboveground leaf biomass by grazing graminivores. This technique supplies sufficient quantities of short chain carbon energy into the rhizosphere initiating the production of large increases in microbe biomass and activity when 60% to 80% of the grass lead tiller population are partially defoliated by grazing graminivores over a period of 7 to 17 days on each pasture during the 45 day stimulation period from 1 June to 15 July.

Initiation of a twice-over strategy on native grassland that had previously been managed by nongrazing or traditional seasonlong practices will have a rhizosphere microbe biomass that is low to very low and it will require about three growing seasons to increase the microbe biomass large enough to mineralize 100 lbs/ac of mineral nitrogen. The response from the rhizosphere microbes is not instantaneous and rhizosphere weight changes respond differently to different management treatments (Manske 2018b).

Management of grassland ecosystems without large grazing graminivores is not sustainable. Forty-five years of research have been devoted to the development of a biologically effective grazing management strategy that can improve and maintain grassland ecosystems at their potential biological levels.

The biologically effective twice-over rotation strategy was designed to coordinate partial defoliation events with grass phenological growth stages, to meet the nutrient requirements of the grazing graminivores, the biological requirements of the grass plants and the rhizosphere microorganisms, to enhance the ecosystem biogeochemical processes, and to activate the internal grass plant growth mechanisms in order for grassland ecosystems to function at the greatest achievable levels.

The twice-over rotation grazing management strategy uses three to six native grassland pastures. Each pasture is grazed for two periods per growing season. The number of grazing periods is determined by the number of sets of tillers: one set of lead tillers and one set of vegetative secondary tillers per growing season. The first grazing period is 45 days long, ideally, from 1 June to 15 July, with each pasture grazed for 7 to 17 days (never less or more). The number of days of the first grazing period on each pasture is the same percentage of 45 days as the percentage of the total season's grazeable forage contributed by each pasture to the complete system. The forage is measured as animal unit months (AUM's). The average grazing season month is 30.5 days long (Manske 2012a). The number of days grazed are not counted by calendar dates but by the number of 24-hr periods grazed from the date and time the livestock are turned out to pasture. The second grazing period is 90 days long, ideally from 15 July to 14 October, each pasture is grazed for twice the number of days as in the first period. The length of the total grazing period is best at 135 days; 45 days during the first period plus 90 days during the second period.

There is some flexibility in the grazing period dates. The starting date has a variance of plus or minus 3 days with a range of start dates from 29 May to 4 June. This gives an extreme early option to start on 29 May with the first period to 12 July and with the second period to 11 October. The extreme late alternative option can start on 4 June with the first period to 18 July and with the second period to 17 October. There is also the option to add a total of 2 days to the total length of the grazing period. These 2 days can be used when a scheduled rotation date occurs on an inconvenient date by adding one day to each of two rotation dates. The limit of additional days is two per year resulting in a total length of 137 days. If inconvenient rotation dates occur during 3 or more times, an equal number of days greater than two must be subtracted from the grazing season, so total number of days grazed per year does not exceed 137 days. If the start date is later than 4 June, the scheduled rotation dates must remain as if the start date were on 4 June, in order to maintain the coordinated match of the partial defoliation events with the grass phenological growth stages. The total number of days grazed will be 135 days minus the number of days from 4 June to the actual start date. However, it is best to start on 1 June each year.

During the first period, partial defoliation that removes 25% to 33% of the leaf biomass from grass lead tillers between the 3.5 new leaf stage and the flower stage increases the rhizosphere microbe biomass and activity, enhances the ecosystem biogeochemical processes, and activates the internal grass plant growth mechanisms. Manipulation of these processes and mechanisms does not occur at any other time during a growing season. During the second grazing period, the lead tillers are maturing and declining in nutritional quality and defoliation by grazing is only moderately beneficial to grass development. Adequate forage nutritional quality during the second period depends on the activation of sufficient quantities of vegetative secondary tillers from axillary buds during the first period. Livestock are removed from intact grassland pastures in mid October, towards the end of the perennial grass growing season, in order to allow the carryover tillers to store the carbohydrates and nutrients which will maintain plant mechanisms over the winter. Most of the upright vegetative tillers on grassland ecosystems during the autumn will be carryover tillers which will resume growth as lead tillers during the next growing season. Almost all grass tillers live for two growing seasons, the first season as vegetative secondary tillers and the second season as lead tillers. Grazing carryover tillers after mid October causes the termination of a large proportion of the population, resulting in greatly reduced herbage biomass production in subsequent growing seasons. The pasture grazed first in the rotation sequence is the last pasture grazed during the previous year. The last pasture grazed has the greatest live herbage weight on 1 June of the following season (Manske 2018a).

Stocking rates are based on peak herbage biomass on seasonlong grazing practices. The starting stocking rate on the "new" twice-over grazing practice is usually 80% to 100% of the seasonlong stocking rate (Manske 2012b). It usually requires three grazing seasons with the twice-over strategy stocked at 100% to increase the rhizosphere microbe biomass to be great enough to mineralize 100 lbs/ac of mineral nitrogen (nitrate NO_3 and ammonium NH_4). After the increased rhizosphere microbe biomass can mineralize 100 lbs/ac of mineral nitrogen, the stocking rate can be increased at 10% per year until the system is stocked at 140% of the seasonlong stocking rate. This has been the maximum biological potential reached on North American grasslands from the twice-over rotation strategy.

Once a rotation date scheduled has been determined, do not change that schedule greater than one day for any worldly reason. If you do not like your neighbors bull, build a fence that the bull cannot jump. If you have water sources that sometimes go dry, put in a water tank system on a pipeline. Fix the problems that develop with solutions that do not change the rotation schedule.

Implementation of a twice-over rotation strategy will activate functionality of the four primary grass physiological growth mechanisms at much higher rates during the summer grazing period of 1 June to 14 October with the availability of 100 lbs/ac mineral nitrogen than the lower grass growth rates on traditional seasonlong practices with inadequate quantities of mineral nitrogen. On the twice-over rotation strategy, the greater than 100 lbs/ac mineral nitrogen result in higher functioning rates of the grass growth mechanisms causing cool season grass lead tiller biomass to be 25.5% greater during the July peak and causing a secondary vegetative tiller biomass to be 50.7% greater during the second peak in September, and causing warm season grass lead tiller biomass to be 29.9% greater during the peak in September and October, which causes total native grass herbage biomass to be 31.2% greater than those on the seasonlong treatment during the growing season. The increased grass biomass and improved nutrient content result in greater stocking rates, with calf weight gain per acre to be 23.0% greater, and cow weight gain per acre to be 46.9% greater than the productivity on traditional seasonlong grazing practices (Manske 2018c).

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Grassland Ecosystems Depend upon the Belowground Processes to Determine the Aboveground Productivity

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Most Northern Plains grasslands are managed by obsolescent grazing practices based on traditional concepts of aboveground plant stewardship that do not address the belowground ecosystem biogeochemical processes nor the belowground grass growth mechanism requirements. Grassland ecosystems cannot achieve productivity or functionality at their biological potential without specifically managing for the belowground processes and mechanisms.

The belowground biogeochemical processes are performed by rhizosphere microorganisms. Grassland soil microflora trophic levels cannot produce their own carbon energy; they lack chlorophyll (achlorophyllous). Also, a large biomass of soil microbes cannot be supported on the small quantities of energy remaining in dead grass roots and leaves. However, grass lead tillers produce large quantities of surplus photosynthate containing short chain carbon energy during vegetative growth stages. This source of carbohydrate energy can be used annually between 1 June and 15 July to feed and sustain a large biomass of rhizosphere microbes (Manske 2018a). The combined weight of the belowground microorganisms on an acre of grassland should be greater than the weight of the largest cow in the herd.

Indispensable Rhizosphere Organisms

The microbial rhizosphere structure is a cylinder of soil particles bonded by fungal secreted adhesive polysaccharides that surrounds active perennial roots of grassland plants growing in intact soils (figure 1) and the cylinder is inhabited by symbiotic resident organisms and frequent regular visiting organisms. The numerous types of rhizosphere microorganisms are organized along a trophic hierarchy with a means of "communication" among the microbes and with the plant (Manske 2018d). The resident organisms are bacteria, protozoa, and endomycorrhizal fungi and the visiting organisms are nematodes, springtails, and mites (Elliot 1978, Anderson et al. 1981, Harley and Smith 1983, Curl and Truelove 1986, Whipps 1990, Campbell and Greaves 1990) and another resident organism is ectomycorrhizal fungi (Caesar-TonThat et al. 2001b, Manske and Caesar-TonThat 2003, Manske 2007b). The numerous types of bacteria have low carbon content. Bacteria are microscopic single celled saprophytic organisms that collectively consume large quantities of soil organic matter and are major primary producers of the rhizosphere (figure 2). Increases in biomass and activity of the bacteria trophic level elevates the concentration of respiratory carbon dioxide (CO_2) resulting in stimulation of activity in the other rhizosphere organisms. Protozoa are single celled microorganisms that are mainly small amoeba in grassland soils and feed primarily on bacteria (figure 3).

The slightly larger rhizosphere organisms are mobile and move among various rhizosphere structures. Nematodes are a diverse group of small nonsegmented worms (figure 4). Most nematodes feed primarily on bacteria or fungi, some feed on protozoa, and some eat other nematodes. Springtails are among the most abundant insect in grassland soils that travel among rhizosphere structures (figure 5). Minute springtails ingest considerable quantities of soil organic matter in order to eat fungi and bacteria. Mites are small eight-legged arachnids that travel among rhizosphere structures and feed on fungi, nematodes, small insects, and other mites. Mites help distribute fungus spores and bacteria through the soil by carrying them on their exoskeleton (figure 6).

Two types of fungi are resident organisms of the rhizosphere; Endomycorrhizal fungi (figure 7) and Ectomycorrhizal fungi (figure 8). Endomycorrhizal fungi are also major primary producers of the rhizosphere and are achlorophyllous saprophytes that live on dead organic matter and cannot fix carbon for energy. Endomycorrhizal fungi develop arbuscules, vesicles, and hyphae within root tissue of the host plant (Harley and Smith 1983) and secrete adhesive polysaccharides that bond soil particles around grass roots forming the structural environment for all rhizosphere organisms. The adhesive polysaccharides also bind soil into aggregates resulting in increased soil pore spaces, increased water holding capacity, and increased rooting depth. Endomycorrhizal fungi also move phosphorus, other macro and micro mineral nutrients, and water through the hyphae to the grass roots for absorption (Moorman and Reeves 1979, Harley and Smith 1983, Allen and Allen 1990, Box and Hammond 1990, Marschner 1992, Koide 1993, Marschner and Dell 1994, Smith and Reed 1997).

Ectomycorrhizal fungi develop a sheath around the grass root with hyphae that do not enter the tissue of the host plant (Harley and Smith 1983) and secrete large amounts of adhesive polysaccharides forming water-stable aggregates in soil that are water permeable but not water soluable. The increased soil aggregation improves soil quality, increases soil oxygenation, increases water infiltration, and decreases erodibility (Caesar-TonThat and Cochran 2000, Caesar-TonThat et al. 2001a, Caesar-TonThat et al. 2001b, Caesar-TonThat 2002, Manske and Caesar-TonThat 2003, Manske 2007).

The bacteria and fungi are the microflora saprotrophic organisms at the bottom of the food chain and makeup the greatest biomass of the rhizosphere. Both bacteria and fungi contain high proportions of nitrogen in relation to their carbon content. The microfauna trophic level organisms with normal ratios of carbon to nitrogen, consume bacteria or fungi and ingest greater quantities of nitrogen than they need for a balanced diet based on energy (carbon); the excess nitrogen is excreted as ammonium (NH_4). The endomycorrhizal fungi can nitrify the excreted ammonium into nitrate (NO_3) and pass either form of mineral nitrogen into the grass plant through its endophytic vesicles and arbuscules. The elevated rhizosphere organism activity caused by the increase in available short chain carbon energy exudated from the grass lead tillers following partial defoliation by graminivores results in greater quantities of organic nitrogen mineralized into inorganic nitrogen (Coleman et al. 1983, Klein et al. 1988, Burrows and Pfleger 2002, Rillig et al. 2002, Bird et al. 2002, Driver et al. 2005).

The response to grazing management practices from the rhizosphere microbes is not instantaneous. Rhizosphere weight changes slowly. Rhizosphere organism biomass and activity are limited by access to short chain carbon energy because the microflora trophic levels lack chlorophyll and cannot capture and fix solar energy. The rhizosphere microbes on the nongrazed control treatment had access to only small quantities of plant material leakage from depauperated grass roots; their six year mean weight was less than 20% of the potential rhizosphere microbe weight. The annual changes in rhizosphere microbe weight on the nongrazed control treatment were small and related to small changes in growing season precipitation during years 1 to 5, with a relatively large change of 50% in microbe weight during year 6 that correspond with a substantial increase in growing season precipitation (figure 9).

The rhizosphere microbes on the twice-over rotation grazing treatment had access to large quantities of carbon energy. Partial defoliation of grass lead tillers at vegetative phenological growth stages by large grazing graminivores causes large quantities of surplus photosynthate that contain short chain carbon energy to be exudated through the grass roots into the rhizosphere providing the needed energy to the rhizosphere organisms. However, even with the increase in grass lead tiller carbon energy, the rhizosphere microbe weights on twice-over rotation managed pastures were not significantly different from those on the nongrazed control during the first two years. The rhizosphere microbe weights did increase by 33% during year 3 on the twice-over grazed pastures and continued to increase at a mean rate of 30.5 kg/m^3 per year from year 3 to 6, reaching a weight of 214.3 kg/m^3, which was 64.2% greater than the microbe weight on the nongrazed control (figure 9). After 6 years of management with the twice-over rotation strategy, the rhizosphere microbes had reached a biomass of 214 kg/m^3 and were mineralizing 99.4 lbs/ac (111.3 kg/ha) of mineral nitrogen (NH_4 and NO_3).

Biogeochemical Processes

The indispensable rhizosphere microorganisms are responsible for the performance of the ecosystem nutrient flow activities and for the ecosystem biogeochemcial processes that determine grassland ecosystem productivity and functionality (Manske 2018d).

Biogeochemical processes transform stored essential elements from organic forms or ionic forms into plant usable mineral forms.

Biogeochemical processes capture replacement quantities of lost or removed major essential elements of carbon, hydrogen, nitrogen, and oxygen with assistance from active live plants and transform the replacement essential elements into storage as soil organic matter for later use.

Biogeochemical processes decompose complex unusable organic material into compounds and then into reusable major and minor essential elements (McNaughton 1979, 1983; Coleman et al. 1983; Ingham et al. 1985; Mueller and Richards 1986; Richards et al. 1988; Briske 1991; Murphy and Briske 1992; Briske and Richards 1994, 1995).

The quantity of biogeochemical processes conducted in grassland ecosystems is dependent on the rhizosphere volume and microorganism biomass (Coleman et al. 1983). Rhizosphere volume and microorganism biomass are limited by access to simple carbohydrate energy (Curl and Truelove 1986). Healthy grass plants produce double the quantity of leaf biomass (Crider 1955, Coyne et al. 1995), capture and fix large amounts of carbon during photosynthesis, and produce carbohydrates in quantities greater than the amount needed for normal growth and maintenance (Coyne et al. 1995). Partial defoliation of grass lead tillers at vegetative phenological growth stages by large grazing graminivores causes greater quantities of exudates containing simple carbohydrates to be released from the grass tillers through the roots into the rhizosphere (Hamilton and Frank 2001). With the increase in availability of carbon compounds in the rhizosphere, the biomass and activity of the microorganisms increases (Anderson et al. 1981, Curl and Truelove 1986, Whipps 1990). The increase in rhizosphere organism biomass and activity results in greater quantities of biogeochemical cycling of essential elements (Coleman et al. 1983, Biondini et al. 1988, Klein et al. 1988, Burrows and Pfleger 2002, Rillig et al. 2002, Bird et al. 2002, Driver et al. 2005).

Major Essential Elements

Perpetuation of life on earth requires that the abiotic major and minor essential elements be reused over and over. Essential elements are required for life to exist by ensuring growth and development of organisms and the maintenance of all life functions. Recycling of the essential elements in grassland soils is performed by rhizosphere microorganisms. The major essential elements required in very large amounts by all animals and plants are: carbon (C), hydrogen (H), nitrogen (N), and oxygen (O). The source of these major essential elements is not the soil but from air and water (Manske 2018d). A major essential element is not part of the grassland ecosystem until it is incorporated into an ecosystem organism. The organic forms of the major essential elements are stored in the soil organic matter SOM (table 1).

Solar radiant energy from the sun is the ecosystem input source for energy. Solar energy reaching the earth's atmosphere that is facing the sun is about 1,365 Watts m^{-2} (Working Group I 2007) with greater amounts at the equator than at the north and south latitudes. Solar energy is captured and stored by autotrophic plants through the chemical process of photosynthesis in chloroplasts where inorganic major essential elements of carbon, hydrogen, and oxygen are synthesized into organic compounds of carbohydrates (CH_2O) (Manske 2018d).

Atmospheric carbon dioxide gas (CO_2) is the ecosystem input source for carbon. Atmospheric carbon dioxide composes about 0.0412% of the gasses in the atmosphere and exists at concentrations of around 385 to 412 ppm (Anonymous 2021a). Carbon dioxide can be obtained directly from air by autotrophic plants in the production of carbohydrates. Carbon reactions in soil produce carbonates and bicarbonates that are readily soluble and available to higher plants. Organic carbon compounds are stored in the soil organic matter. Increases in soil organic carbon SOC improve nutrient storage, increase water holding capacity, and enhance aggregation (Manske 2018d).

Soil water (H_2O) is infiltrated precipitation water and is the ecosystem input source for plant water, hydrogen ions (H+) and hydroxyl ions (OH-). Soil air contains higher concentrations of water vapor (H_2O) than the atmosphere. Hydrogen ions (H+) and hydroxyl ions (OH-) are released into the soil during the early stages of soil organic matter decomposition (Manske 2018d).

Atmospheric nitrogen gas (N_2) is the original input source for ecosystem nitrogen. Atmospheric nitrogen (N_2) composes about 78.084% of the gasses in the atmosphere. The bonds of atmosphere nitrogen are strong and make N_2 gas inert to most higher organisms. The high temperature of a lightning bolt at 50,000 F (28,000 C) can break these nitrogen bonds. Free nitrogen atoms in the air bond with oxygen to create nitrogen oxides (NO, NO_2), which dissolve in water to form ammonium (NH_4) and nitrate (NO_3) in soil. The global lightning production of nitrogen atoms is estimated at 1 to 20 Tg N yr^{-1} (Tg=Tera trillion 10^{12} g) (Anonymous 2021b) which is, in the temperate zone, about 5 to 6 pounds of nitrogen per acre per year (Brady 1974, Gibson 2009). A net accumulation of 2 pounds of nitrogen per acre per year results in a soil with 5 tons of nitrogen per acre in 5000 years. Most of the nitrogen in soils is stored in the soil organic matter SOM as organic nitrogen that is unavailable to plants. Northern Plains intact soils contain around 3 to 8 tons of organic nitrogen per acre. Rhizosphere microorganisms mineralize organic nitrogen into inorganic nitrogen in forms of ammonium (NH_4) and nitrate (NO_3) which are available to plants and are the source of nitrogen for plant growth (Manske 2018d).

Atmospheric oxygen gas (O_2) is the ecosystem input source for oxygen. Atmospheric oxygen composes about 20.946% of the gases in the atmosphere. Oxygen can be obtained directly from the air by autotrophic plants. Oxygen is usually at lower concentrations in soil air. Respiration of plant roots can directly use the oxygen in soil air. Aerobic decomposition of organic residue by microbes can directly use the oxygen in soil air. Oxidation of organic carbonaceous compounds produces carbon dioxide (CO_2) that is emitted from soils into the atmosphere. Plant photosynthetic rates during the growing season remove greater quantities of carbon dioxide from the atmosphere than the quantities of CO_2 emissions (Manske 2018d).

Minor Essential Elements

The minor essential elements are the macronutrients required in large amounts and the micronutrients required in very small amounts. The source of all the minor essential elements is weathered soil parent material. The minor essential elements are stored in the soil organic matter as unavailable organic forms or as ions adsorbed by colloidal complexes and are biologically and chemically immobilized, respectively. While in these stable forms, the minor essential elements are not subjected to potential losses through volatilization or leaching movement (Legg 1975, Gibson 2009). The immobilized minor essential elements are made available through the ecosystem biogeochemical cycles performed by rhizosphere microorganisms (McGill and Cole 1981, Cheng and Johnson 1998, Manske 2012, 2014). The quantity of available minor essential elements is determined by the recycling rates of soil organic matter decomposition and mineralization that are directly regulated by the biomass of active rhizosphere microorganisms (Manske 2018d).

Animals and plants require large amounts of the same macronutrients: potassium (K). calcium (Ca). phosphorus (P), magnesium (Mg), and sulfur (S). Animal require an additional macronutirent: sodium (Na) and require chlorine (Cl) as a macronutrient. Warm season plants and cacti use some sodium (Na). Animals and plants require very small amounts of the same micronutrients or trace elements: iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), and nickel (Ni). Animals require additional micronutrients: iodine (I), cobalt (Co), selenium (Se), and chromium (Cr). Plants require an additional micronutrient: boron (B), and require chlorine (Cl) as a micronutrient. A few plants and rhizobia use some cobalt (Co) (table 1) (Manske 2018d).

Indispensable Grass Vegetation

Grass plants use the major and minor essential elements in the inorganic form to synthesize vital organic compounds of carbohydrates, proteins, and nucleotides for growth. Grass tillers consist of shoots and roots (figure 10). The shoot is the stem and leaves comprised of repeated phytomers (Beard 1973, Dahl 1995). A phytomer consists of a leaf, with a blade and a sheath separated by a collar, along with a node, an internode, and an axillary bud (Hyder 1974, Dahl and Hyder 1977). Each tiller shoot generally produces 6 to 8 phytomers per growing season (Langer 1972, Dahl 1995).

Almost all tillers live for two growing seasons. During the first growing season, grass tillers can produce 6 to 8 leaves and remain vegetative. During the second growing season, grass lead tillers produce a second set of 6 to 8 leaves plus development of flowers and seeds. At the end of each growing season, all tillers deactivate the chlorophyll and turn a tan color. Lead tillers that had produced flowers are terminal. Vegetative tillers remain alive through the winter by burning carbohydrates that had been stored during the winter hardening period. By spring, these carbohydrate reserves are nearly depleted and not adequate to support both root and new leaf growth (Manske 2011). Chlorophyll is reactivated during early spring in parts of old previous years leaves where the cells had not ruptured. Usually, each carryover tiller has 2 or 3 previous years leaves that are half tan and half green. The green portions of the carryover leaves photosynthesize the material that will be used to produce the new current years leaves. New leaves of these second year lead tillers grow straight up from the apical meristem, located at the tiller base, through the old leaf sheaths until it reaches full size, then it tips to one side of the tiller and so on. After three new full size leaves and a fourth new leaf growing straight up about half size have been produced; that lead tiller is at the three and a half new leaf stage and has sufficient leaf area to provide the photosynthetic assimilates for additional new growth. The old carryover leaves at that stage are no longer required and will completely dry in a short time (Manske 2011). These old carryover leaves should never be counted as new current years leaves (Manske 2019b).

Grass Growth Mechanisms

The key factor in meeting grass growth mechanism biological and physiological requirements is proper coordinated timing of partial defoliation with grass plant phenological growth stages. The grass growth mechanisms are triggered by seasonable partial defoliation by large grazing graminivores of grass lead tillers during phenological growth between the three and a half new leaf stage and the flowering (anthesis) stage; for native grass this occurs between 1 June and 15 July each growing season (Manske 2011). The effects of partial defoliation are not simply the removal of some herbage from grass plants (Langer 1963, 1972): foliage removal disrupts plant growth and photosynthesis, and partial defoliation also changes physiological mechanisms in all parts of the plant; alters the plant community microclimate by changing light transmissions, moisture relations, and temperature (Briske and Richards 1994, 1995); and changes the soil environment, thereby affecting soil microorganism activity and ecosystem biogeochemcial processes (Manske 2000, 2011). Internal grass growth mechanisms help grass tillers withstand and recover from partial defoliation by grazing graminivores. The four primary physiological grass growth mechanisms are: compensatory physiological mechanisms, vegetative reproduction by tillering, nutrient resource uptake competitiveness, and water use efficiency (Manske 2018a, c).

The compensatory physiological mechanisms give grass tillers the capability to replace lost leaf and shoot biomass following grazing by increasing meristematic tissue activity, increasing photosynthetic capacity, and increasing allocation of carbon and nitrogen (McNaughton 1979, 1983; Briske 1991). Fully activated mechanisms can produce replacement foliage at 140% of the weight that was removed during grazing (Manske 2009).

Vegetative secondary tillers are shoots that develop on lead tillers from growth of axillary buds (figure 11). Each tiller has one axillary bud for each of the 6 to 8 new current years leaves. This growth and subsequent development of vegetative tillers is regulated by auxin, a growth-inhibiting hormone produced in the apical meristem and young leaves. Partial defoliation of young leaf material at vegetative growth stages temporarily reduces the quantity of auxin which then allows cytokinin, a growth hormone, to stimulate the meristematic tissue of multiple axillary buds to develop into vegetative secondary tillers (Mueller and Richards 1986, Richards et al. 1988, Murphy and Briske 1992, Briske and Richards 1994, 1995).

Nutrient resource uptake competitiveness determines the level of grass plant dominance within a grassland community. Removal of aboveground leaf material from grass plants affects root functions. Removal of 50% or more leaf material greatly reduces root growth, root respiration, and root nutrient and water absorption resulting in severe degradation of the functionality of grass plants (Crider 1955). Reduction of active root biomass causes diminishment of grass plant health and vigor (Whitman 1974) that result in a loss of resource uptake efficiency and a suppression of the competitiveness of grass plants to take up mineral nitrogen, essential elements, and soil water. Reduction of grass plant nutrient uptake competitiveness allows successful establishment of undesirable grasses, weedy forbs, and shrub seedlings and rhizomes into grassland communities (Li and Wilson 1998, Kochy 1999, Kochy and Wilson 2000, Peltzer and Kochy 2001).

Water use efficiency in grass plants is not at a simple constant rate. Precipitation (water) use efficiency of grass plants improves when soil mineral nitrogen is available at threshold quantities of 100 lbs/ac (112 kg/ha) and greater. The inhibitory deficiencies of mineral nitrogen on grasslands managed with traditional practices are notorious for causing the observed low herbage production (Goetz et al. 1978). Grasslands that have less than 100 lbs/ac of available soil mineral nitrogen cause the weight of herbage production per inch of precipitation received to be reduced an average of 49.6% below the weight of herbage produced per inch of precipitation on the grassland ecosystems that have greater than 100 lbs/ac of mineral nitrogen (Wight and Black 1972, 1979).

The vegetative reproduction by tillering and the compensatory physiological mechanisms function at remarkably high rates on grasslands that have greater than 100 lbs/ac of available mineral nitrogen and these mechanisms do not function or function at extremely low rates on grasslands that have mineral nitrogen deficiencies at less than 100 lbs/ac (Manske 2009, 2014, 2018d).

Sustaining functionality of the four primary physiological grass growth mechanisms at high production rates requires annual partial defoliation by grazing graminivores that removes 25% to 33% of leaf weight from 60% to 80% of the grass lead tillers between the three and a half new leaf stage and the flower stage (1 June to 15 July) with mineral nitrogen available at 100 lbs/ac or greater (Manske 1999, 2014, 2018a). Rhizosphere microorganisms with a high biomass at 363 to 689 lbs/yd^3 (214 to 406 kg/m^3) can mineralize 99.4 to 157.4 lbs/ac (111.3 to 176.3 kg/ha) of mineral nitrogen (Manske 2018d). After mid July, herbage removal can be increased to 50% of the grass tiller total aboveground herbage weight.

Grass growth and development phenological stages are triggered primarily by length of daylight (Roberts 1939, Dahl 1995). In the northern hemisphere, daylight hours increase during the growing season between mid April and 21 June and then decrease at the same rate of change each year. Grazing forage plants is more efficient and effective when the phenological growth stages, the herbage production curves, and the nutrient quality curves of the forage sources match the biological and physiological requirements of the grazing livestock. This coordination between the primary producers and the primary consumers is a very old concept called "seasonality" (Manske 2018f).

Grass Seasonality Grazing Periods

The critical three and a half new leaf stage is the phenological growth stage when grass lead tillers become physiologically capable of being grazed (Manske 1999). Not all grass species develop this critical phenological leaf stage at the same time nor at the same length of daylight. However, the critical three and a half new leaf stage does develop during only three different seasonality grazing time periods of which all perennial grasses that can grow in the Northern Plains can be categorized to fit into one of these three seasonality time periods.

The spring seasonality grazing period is when the first grass types develop three and a half new leaves at slightly before or near 1 May. The grasses in this category are the domesticated cool season grasses (crested wheatgrass and smooth bromegrass). The period when the rhizosphere biomass can be increased and the ecosystem biogeochemical processes and the grass growth mechanisms can be activated is 1 to 28 May. The recommended grazing start date for the spring seasonality period is 1 May and the recommended grazing period for the domesticated cool season grass complementary spring pastures is from 1 to 31 May (Manske 2017c, d).

The summer seasonality grazing period is when the second and third grass types develop three and a half new leaves. The native cool season grasses develop the critical new leaf stage just before, on, or near 1 June. The native warm season grasses develop the critical new leaf stage during mid June. The period when the rhizosphere biomass can be increased and the ecosystem biogeochemical processes and the grass growth mechanisms can be activated is 1 June to 15 July. The recommended grazing start date for the summer seasonality period is 1 June and the recommended grazing period for the native grass summer grazing period is from 1 June to 14 October (Manske 2018b, f).

The fall seasonality grazing period is when the fourth grass types develop three and a half new leaves during early June. The grasses in this category are extremely different biologically than other grasses and are the wildryes (Altai and Russian). They act more like perennial winter cereals. The period when the grass growth mechanisms can be activated is during the fall (mid October to mid November). Wildryes develop severe negative affects when managed by the same traditional practices as the domesticated cool season grasses or the native cool and warm season grasses. The recommended grazing start date for the fall seasonality period is mid October and the recommended grazing period for the wildye complementary fall pastures is from mid October to mid November with a mandatory practice of leaving no less than 50% of the residual herbage biomass (Manske 2017a, b). By leaving 50% residual vegetation annually is the only practice that can maintain the great potential herbage production levels. Removal of greater than 50% of the residual herbage results in harsh reductions in annual productivity and causes stand loss in 20 to 25 years (Manske 2018f).

There is no winter seasonality grazing period because there are no perennial grasses that can grow in the Northern Plains and provide adequate quantities of crude protein for grazing modern high performance range cows during the 5.5 month winter season (mid November through the end of April). Low cost, high quality harvested forage strategies can be successfully used to provide livestock food during the winter seasonality feeding period (Manske 2019a).

Indispensable Grazing Graminivores

Grazing graminivores receive nutritious forage from healthy grass plants. Providing forage for graminivores is not the only purpose for grazing grasslands. Grazing graminivores is biologically beneficial for grass plants and indispensable for grassland ecosystems when grazing periods are coordinated with grass phenological growth stages. The essential rhizosphere microorganisms are achlorophyllous and cannot capture and fix their own energy, and the small quantity of short chain carbon energy naturally leaked from grass plants is too low to support any greater than a tiny biomass of soil microbes. However, partial defoliation by large graminivores of grass lead tillers at vegetative growth stages cause the exudation of large quantities of short chain carbon energy from grass lead tillers through the roots to the rhizosphere microbes. The resulting greater biomass and activity of the soil microbes can transform greater quantities of unusable essential elements from the organic form or ionic form into a plant usable form. A large biomass of rhizosphere microorganisms is required to mineralize a large quantity of unusable organic nitrogen into a threshold yield of 100 lbs/ac of available mineral nitrogen in the forms of ammonium (NH_4) and nitrate (NO_3). The activity of the large biomass of rhizosphere microbes are able to perform all of the ecosystem biogeochemical processes.

Grass growth can occur without partial defoliation by grazing graminivores, however, total herbage biomass production is greatly suppressed without the activation of the grass growth mechanisms of compensatory physiological mechanisms, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency. These four primary physiological grass growth mechanisms that perform the herbage replacement processes are activated with partial defoliation by large grazing graminivores when 25% to 33% of leaf weight is removed from 60% to 80% of lead tillers during vegetative phenological growth stages between the three and a half new leaf stage and the flower stage. When a threshold quantity of 100 lbs/ac of mineral nitrogen is available in the soil and all four grass growth mechanisms are fully activated, grass tillers can produce 140% of the quantity removed from the foliage by grazing which would not have been produced without partial defoliation by grazing graminivores. The replacement herbage produced by the activated grass growth mechanisms will provide adequate quantities of crude protein for the cows between mid July and late September 100% of the years and to mid October 64% of the years (Manske 2018f).

Grazing graminivores remove the 50% surplus grass biomass produced by grass plants before that extra herbage can become detrimental to the ecosystem each growing season. There are no replacement management practices that can perform the indispensable functions that grazing graminivores provide to fully functional grassland ecosystems (Manske 2018e).

Modern Range Cow

The North American beef herd has been transformed over the last half century into high-performance, fast-growing meat animals with improved genetic potential, and increased nutrient demands. A high performance 1200 lb range cow with average milk production at 20 lbs/d, is 20% larger than an old style 1000 lb range cow that had milk production at 12 to 6 lbs/d, and requires 27% more energy and 41% more crude protein per day during the lactation production periods than the old style range cow (Manske 2018f). Improved animal genetics was intended to solve the problems in the beef industry. Unfortunately, the forage management technology was not improved simultaneously with beef cow performance.

Evaluation of Seasonality Management

Grass and livestock performance on two different management concepts were evaluated. The standard Traditional concept managed the aboveground grassland resources for their use as forage for livestock. The Biologically Effective concept managed the above- and belowground grassland resources as functional ecosystems and considered the biological requirements of the grass plants, soil microbes, and the livestock.

Pasture costs were determined using pasture rent values of $8.76 per acre which was the mean rent of 15 counties in southwestern North Dakota reported for 1993 and 1994 (ND Ag Statistics). Market value per pound of calf pasture accumulated live weight gain was determined from the low market value of $0.70 per pound occurring during the study years of 1993 and 1994. Commercial crossbred cattle were used on all grazing treatments. Calves were born during March and early April with average birth dates of 16 March and average birth weight of 95 pounds, and average weight gain between birth and pasture turn out was 95 pounds. Before spring turn out, cow-calf pairs were sorted by cow age and calf age with 50% steers and heifers. Average cow weight at spring turn out was between 1100 lbs and 1200 lbs (Manske 2018f).

Most of the calves were more than a month old on 1 May and could gain greater weight than 1.5

lbs/day which is about the maximum rate of gain for calves less than 1 month old. The calves older than 1 month on 1 May maintained rapid growth rates through to finish. The calves that were younger than 1 month old on 1 May had lower rates of gain and never caught up with the older calves.

The natural beef cow breeding season in the Northern Plains is 1June to 15 July when native grass plants have their greatest nutrient content. Cows with calves 1 month old on 1 May and grazed crested wheatgrass pastures had two months of high quality forage to reach their peak lactation by 31 May.

Bison do not follow the beef cattle strategy. Bison arrived in North America a million years ago and their natural breeding season during August is not an advantageous model to match for domesticated beef animals because the bison herd enlarges when only 25% of the bison cows wean a live calf. August breeding of beef cows can result in many open cows. Having several or even a few modern high performance beef cows open in a herd each year has an extreme high cost that is hard to recover. Cows that do calve late during May and early June usually do not reach their genetic peak lactation or cannot maintain high lactation for more than a short 2 week period, and their calves do not gain weight at their genetic potential rates.

Traditional Standard Management

The traditional spring seasonality complementary pasture was crested wheatgrass. Cow and calf pairs grazed one unfertilized pasture of 15 acres (replicated three times) at 2.33 ac/AUM for 28 days (2.14 ac/AU) from early May to early June.

The traditional summer seasonality rangeland pasture was northern mixed grass prairie. Cow and calf pairs grazed one native rangeland pasture seasonlong (replicated two times) with 7 cows per 80 acres at 2.58 ac/AUM for 135 days (11.43 ac/AU) from early June to mid October.

The traditional fall seasonality complementary perennial grass pasture was reserve native rangeland. Cow and calf pairs grazed one pasture of native rangeland (replicated two times) at 4.11 ac/AUM for 30 days (4.04 ac/AU) from mid October to mid November (Manske 2018f).

Biologically Effective Management

The biologically effective spring seasonality complementary pasture was crested wheatgrass. Cow and calf pairs grazed one unfertilized pasture of 26.5 acres split into equal halves with each portion grazed during 2 alternating 7 day periods in a switchback plan (replicated two times) at 1.30 ac/AUM for 28 days (1.20 ac/AU) from early May to early June. The switchback management plan is described in Manske 2018f.

The biologically effective summer seasonality rangeland pastures were northern mixed grass prairie. Cow and calf pairs grazed three native rangeland pastures with a twice-over rotation system (replicated two times) with 8 cows per 80 acres at 2.26 ac/AUM for 135 days (10.22 ac/AU) from early June to mid October. The twice-over rotation management strategy is described in Manske 2018f.

The biologically effective fall seasonality complementary perennial grass pasture was Altai wildrye. Cow and calf pairs grazed one pasture of Altai wildrye (replicated two times) at 1.41 ac/AUM for 30 days (1.39 ac/AU) from mid October to mid November leaving 50% residual herbage at the end of grazing (Manske 2018f). The current strategy for grazing fall wildrye pastures is described in Manske 2018f.

Seasonality Spring, Summer, and Fall Pastures

This evaluation of seasonality systems compares cow and calf weight performance and net returns from spring, summer, and fall pastures that are managed by two distinctly different concepts.

On the Traditional Standard concept system, cow and calf pairs grazed one crested wheatgrass pasture at the rate of 2.14 acres for 28 days during 4 May to 1 Jun, one seasonlong native rangeland pasture was grazed at the rate of 11.43 acres for 135 days during 1 Jun to 14 Oct, and one reserved native rangeland pasture was grazed at the rate of 4.04 acres for 30 days during 14 Oct to 13 Nov. The entire growing season system was comprised of 17.61 acres per cow-calf pair grazed for 193 days (6.33 months) from 4 May to 13 Nov at a total pasture cost of $154.27 per cow-calf pair, with a cost of $0.80 per day (table 2). Calf weight gain was 444.77 lbs per head, 2.30 lbs per day, and 25.26 lbs per acre (table 4). Cow weight gain was 74.06 lbs per head, 0.38 lbs per day, and 4.21 lbs per acre (table 4). The dollar value captured was $311.34 calf pasture weight gain value, $157.07 net return per cow-calf pair, $8.92 net return per acre, and $0.35 cost per lb of calf weight gain (table 4).

On the Biologically Effective concept system, cow and calf pairs grazed two switchback crested wheatgrass pastures at a rate of 1.20 acres for 28 days during 4 May to 1 Jun, three twice-over rotation native rangeland pastures were grazed at a rate of 10.22 acres for 135 days during 1 Jun to 14 Oct, and one Altai wildrye pasture was grazed at a rate of 1.39 acres for 30 days during 14 Oct to 13 Nov leaving 50% herbage residual each year. The entire growing season system was comprised of 12.81 acres per cow-calf pair grazed for 193 days (6.33 months) from 4 May to 13 Nov at a total pasture cost of $112.22 per cow-calf pair, with a cost of $0.58 per day (table 3). Calf weight gain was 507.26 lbs per head, 2.63 lbs per day, and 39.88 lbs per acre (table 5). Cow weight gain was 204.95 lbs per head, 1.06 lbs per day, and 16.11 lbs per acre (table 5). The dollar value captured was $355.09 calf pasture weight gain value, $242.86 net return per cow-calf pair, $18.96 net return per acre, and $0.22 cost per lb of calf weight gain (table 5).

The grazing periods occurred at the same time on the same types of vegetation, the number of days grazed were the same on both growing season concept systems. The Biologically Effective concept grazed 4.80 fewer acres, at $42.05 lower cost per cow-calf pair, and at $0.22 lower cost per day (tables 2 and 3). On the Biologically Effective concept system, calf weight gain was 62.49 lbs per head greater, 0.33 lbs per day greater, and 14.62 lbs per acre greater than those on the Traditional concept, cow weight gain was 130.89 lbs per head greater, 0.68 lbs per day greater, and 11.90 lbs per acre greater than those on the Traditional concept (tables 4 and 5). The dollar value captured on the Biologically Effective concept system was $43.75 greater calf pasture weight gain value, $85.79 greater net returns per cow-calf pair, $10.04 greater net return per acre, and $0.13 lower cost per lb of calf weight gain than those on the Traditional concept (tables 4 and 5).

Using the Traditional Standard concept of management, a herd of 400 cow-calf pairs would require a total of 7,044 acres, for spring (856 ac), summer (4572 ac), and fall (1616 ac) pastures, at a cost of $61,708, that would yield $62,828 per year. Using the Biologically Effective concept of management, a herd of 400 cow-calf pairs would require a total of 5,124 acres, for spring (480 ac), summer (4088 ac), and fall (556 ac) pastures, at a cost of $44,888, that would yield $97,144 per year. A herd of 400 cow-calf pairs managed during the growing season with the Biologically Effective concept would require 1,920 fewer acres, at $16,820 lower pasture costs, and yielded $34,316 greater (54.6%) net returns for the cow-calf pairs than those on the Traditional concept.

On the Traditional concept, crested wheatgrass herbage biomass during May was 1261 lbs/ac and the calves gained 32.93 lbs/ac during spring seasonality period (figure 12, tables 4 and 6). On the Biologically Effective concept, crested wheatgrass herbage biomass during May was 2183 lbs/ac (73.1% greater) and the calves gained 66.60 lbs/ac during spring seasonality period (102.3% greater) (figure 12, tables 5 and 7).

On the Traditional concept, native rangeland grass lead tillers had peak herbage during July at 851 lbs/ac and did not have a second peak of vegetative tillers during September with herbage at 771 lbs/ac, with crude protein levels below cow requirements from mid July, and the calves gained 30.61 lbs/ac during the summer (figure 13, tables 4 and 6). On the Biologically Effective concept, native rangeland grass lead tillers had peak herbage during July at 1065 lbs/ac (25.1% greater) and the vegetative tillers had a second peak during September at 1128 lbs/ac (46.3% greater), with crude protein levels at or above cow requirements the entire summer period, and the calves gained 37.66 lbs/ac during the summer (23.0% greater) (figure 13, tables 5 and 7).

On the Traditional concept, fall reserve pasture herbage was at 891 lbs/ac, with crude protein levels below cow requirements the entire fall period, and the calves gained 4.38 lbs/ac during fall seasonality period (tables 4 and 6). On the Biologically Effective concept, fall Altai wildrye pasture herbage was at 3141 lbs/ac (252.5% greater), with crude protein levels at or above cow requirements the entire fall period, and the calves gained 37.12 lbs/ac during fall seasonality period (747.5% greater) (figure 14, tables 5 and 7).

The Biologically Effective concept during the spring seasonality period produced 73.1% greater herbage biomass, 102.3% greater calf weight per acre, 145.6% greater cow weight per acre, had 33.9% greater net return per cow-calf pair, had 138.9% greater net return per acre, and had 43.9% lower cost per cow-calf pair than those on the Traditional Standard concept.

The Biologically Effective concept during the summer seasonality period produced 25.1% greater lead tiller herbage peak in July and 46.3% greater vegetative tiller herbage peak in September, with adequate crude protein the entire summer period, 23.0% greater calf weight per acre, 46.9% greater cow weight per acre, had 19.5% greater net return per cow-calf pair, had 33.7% greater net return per acre, and had 10.6% lower cost per cow-calf pair than those on the Traditional Standard concept.

The Biologically Effective concept during the fall seasonality period produced 252.5% greater herbage biomass, with adequate crude protein the entire fall period, 747.5% greater calf weight per acre, 349.8% greater cow weight per acre, had 200.4% greater net return per cow-calf pair, had 391.6% greater net return per acre, and had 65.6% lower cost per cow-calf pair than those on the Traditional Standard concept.

Summary Conclusion

Livestock producers have improved the genetic potential productivity of the North American beef herd, but did not simultaneously improve the forage management technologies. Along with larger size and increased production, the animal nutritional demands have greatly increased. The high performance modern cow's requirements for crude protein during lactation have increased 41% to 72%, depending on the quantity of milk produced, greater than that required by the old style cows. The old traditional concepts of pasture management have not been able to provide the increased levels of nutrients required by modern cows. Improvements of the forage management paradigms consider the biological requirements of the grass plants, the soil microbes, and the livestock and manage the above - and belowground resources as functional ecosystems.

Biogeochemical processes and grass growth mechanisms exist in grassland ecosystems that have the ability to produce larger quantities of herbage biomass at greater nutritional quality that can meet modern cow requirements during lactation to the end of the growing season when the grazing management practices are coordinated with grass phenological growth stages and designed to activate these processes and mechanisms instead of shutting them down as with the old traditional concepts.

Soil microorganisms perform the ecosystem biogeochemical processes that transform organic nitrogen and other essential elements that are in forms not available for plant use into the mineral or ionic forms that are available for plant growth. These ecosystem processes require a large biomass of active soil microorganisms. Grassland soil organisms cannot get enough energy from dead grass parts and they cannot photosynthesize their own energy. Fortunately, grass lead tillers in vegetative growth stages produce surplus carbon energy that can be manipulated to be released through the roots to feed the soil microbes when partial defoliation by grazing graminivores remove 25% to 33% of the lead tiller weight each year during grass phenological growth stages between the 3.5 new leaf stage and the flower stage, which occurs on native grasslands between 1 June and 15 July. The microorganisms use the grass carbon energy to multiply and increase their biomass. The microbes must increase to a great enough biomass that can transform organic nitrogen into the threshold quantity of 100 lbs/ac of available mineral nitrogen or greater.

Partial defoliation by grazing graminivores during the only stimulation period each growing season, feeds lead tiller surplus carbon energy to the soil microbes, and activates both the ecosystem biogeochemical processes, and the four primary grass growth mechanisms. With the ecosystem processes and growth mechanisms functioning at biological potential levels, the quantity of herbage biomass production is greatly increased and the higher nutritional quality of the forage meets the modern lactating cows requirements and the calves gain weight at their genetic potential.

Acknowledgment

I am grateful to Sheri Schneider for assistance in production of this manuscript and for development of the tables and figures.

RHIZOSPHERE STRUCTURE

Figure 1. Rhizosphere with soil particles bound to plant roots by polysaccharides secreted by mycorrhizal fungi.

MICROFLORA

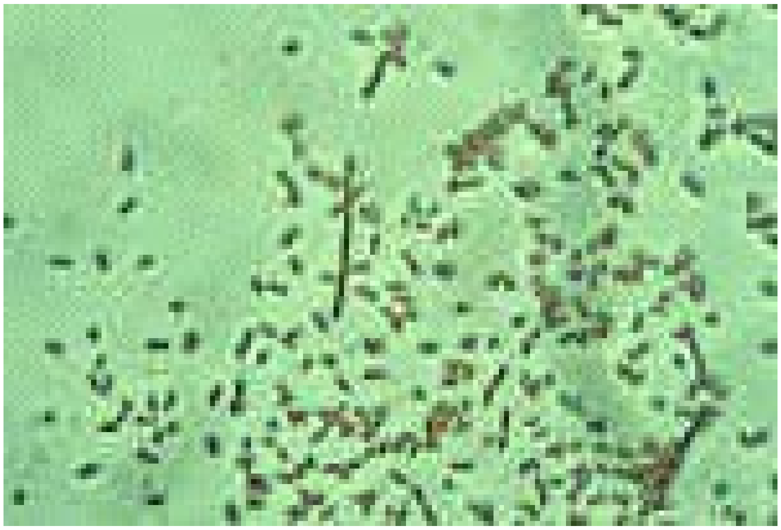

Photo from M.T. Holmes

Figure 2. Bacteria are microscopic single-celled organisms with biomass greater than 2000 pounds per acre.

MICROFAUNA

PROTOZOA

Photo from J.P. Martin

Figure 3. Amoeba ingesting bacteria.
Protozoa are single-celled microorganisms.

NEMATODES

Photo from H. Garrett

Figure 4. Beneficial nematodes are small nonsegmented worms.

SPRINGTAILS

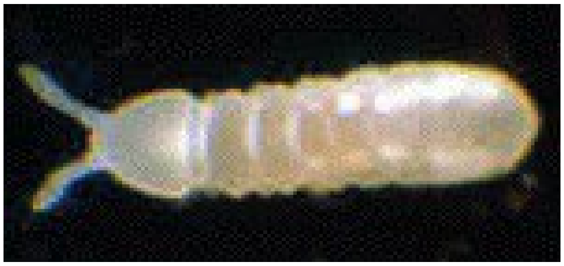

Photo from A.R. Moldenke

Blind fungal-feeding springtail.

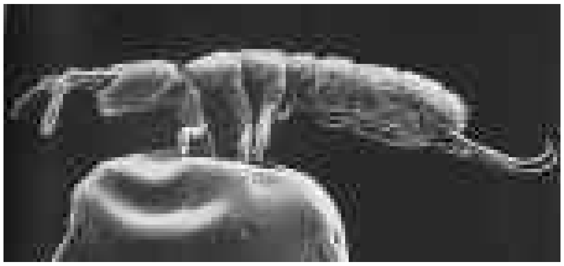

Photo from G. Eisenbeis and W. Wichard

Springtail with furcula released.

Fig ure 5. Springtails are minute insects.

MITES

Photo from G. Eisenbeis and W. Wichard

Predatory mite.

Figure 6. Mites are small eight-legged arachnids.

MYCORRHIZAL FUNGI

Figure 7. ENDOMYCORRHIZAL FUNGI

Photo from R. Campbell

Fungal hyphae strands with bacteria on the surface.

Photo from M. Brundrett

Arbuscules and vesicles of a mycorrhizal fungus within root tissue.

Figure 8. ECTOMYCORRHIZAL FUNGI

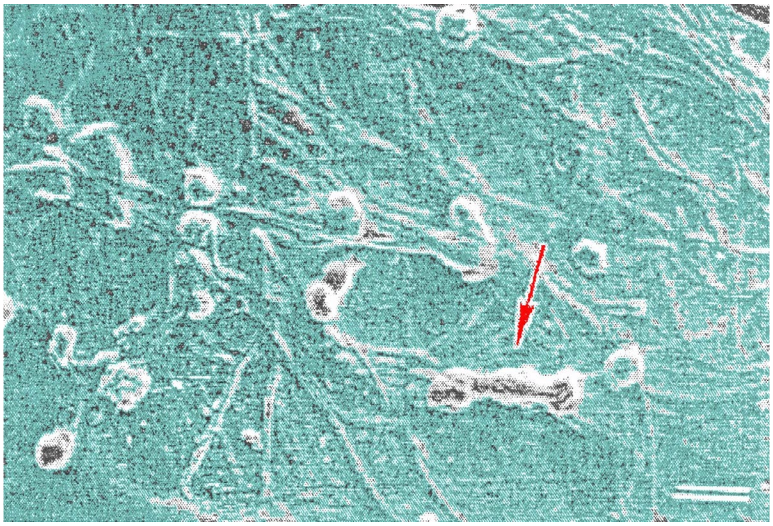

Photo from T.C. Caesar-TonThat

Ectomycorrhizal fungus with extracellular polysaccharides.

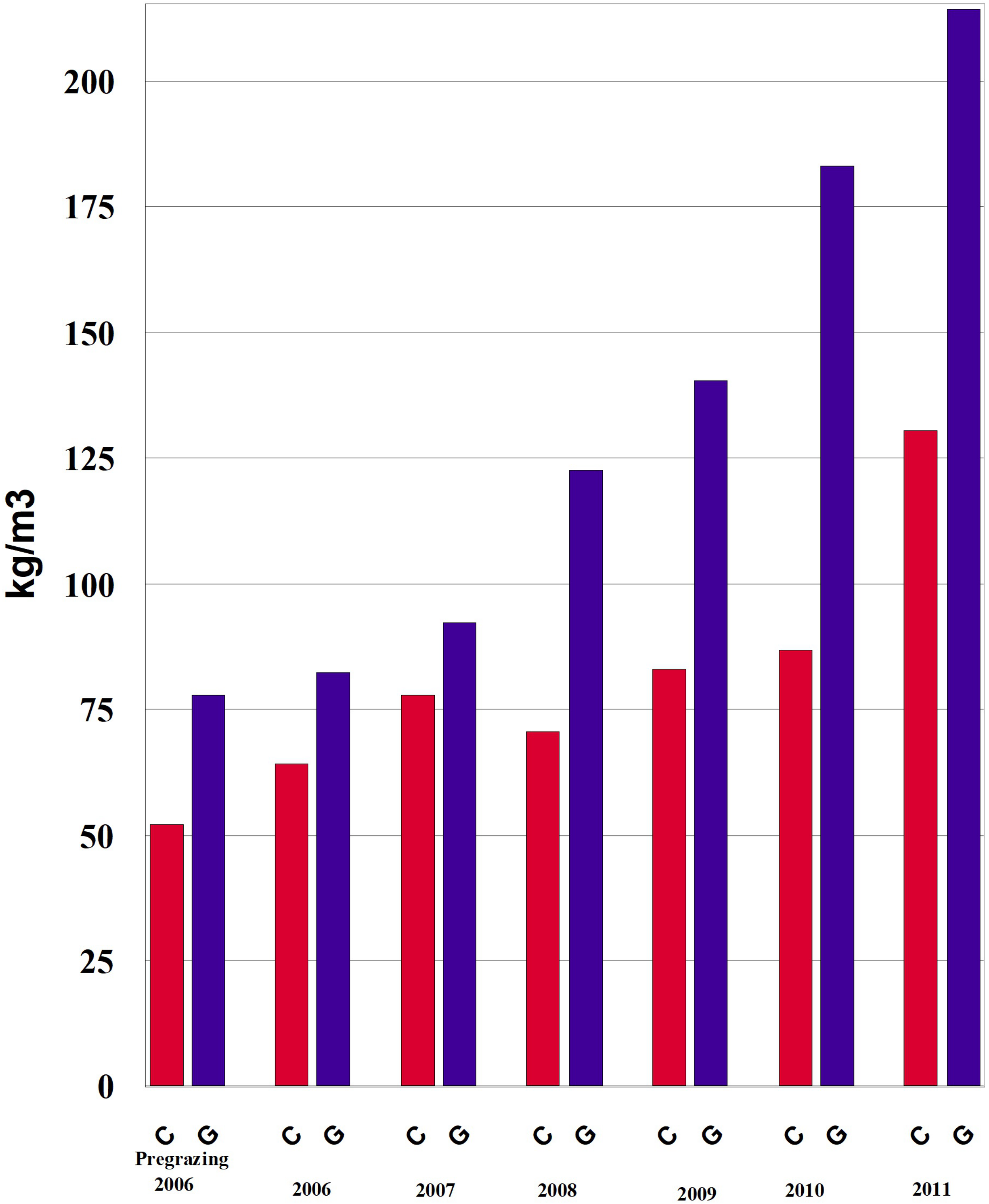

Figure 9. Rhizosphere weight (kg/m3) for the control pasture (red) and grazed pastures (blue) during six years of twice-over rotation management, 2006-2011.

Table 1. Essential Elements Required by Animals and Plants.

Major Essential Elements required by animals and plants

Carbon (C), Hydrogen (H), Nitrogen (N), Oxygen (O)

Minor Essential Elements

Macronutrients required by animals and plants

Potassium (K), Calcium (Ca), Phosphorus (P), Magnesium (Mg), Sulfur (S)

Macronutrients required by animals

Sodium (Na), Chlorine (Cl)

Micronutrients required by animals and plants

Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu)

Molybdenum (Mo), Nickel (Ni)

Micronutrients required by animals

Iodine (I), Cobalt (Co), Selenium (Se), Chromium (Cr)

Micronutrients required by plants

Boron (B), Chlorine (Cl)

Blue elements required by both animals and plants, Red elements required by animals, Green elements required by plants.

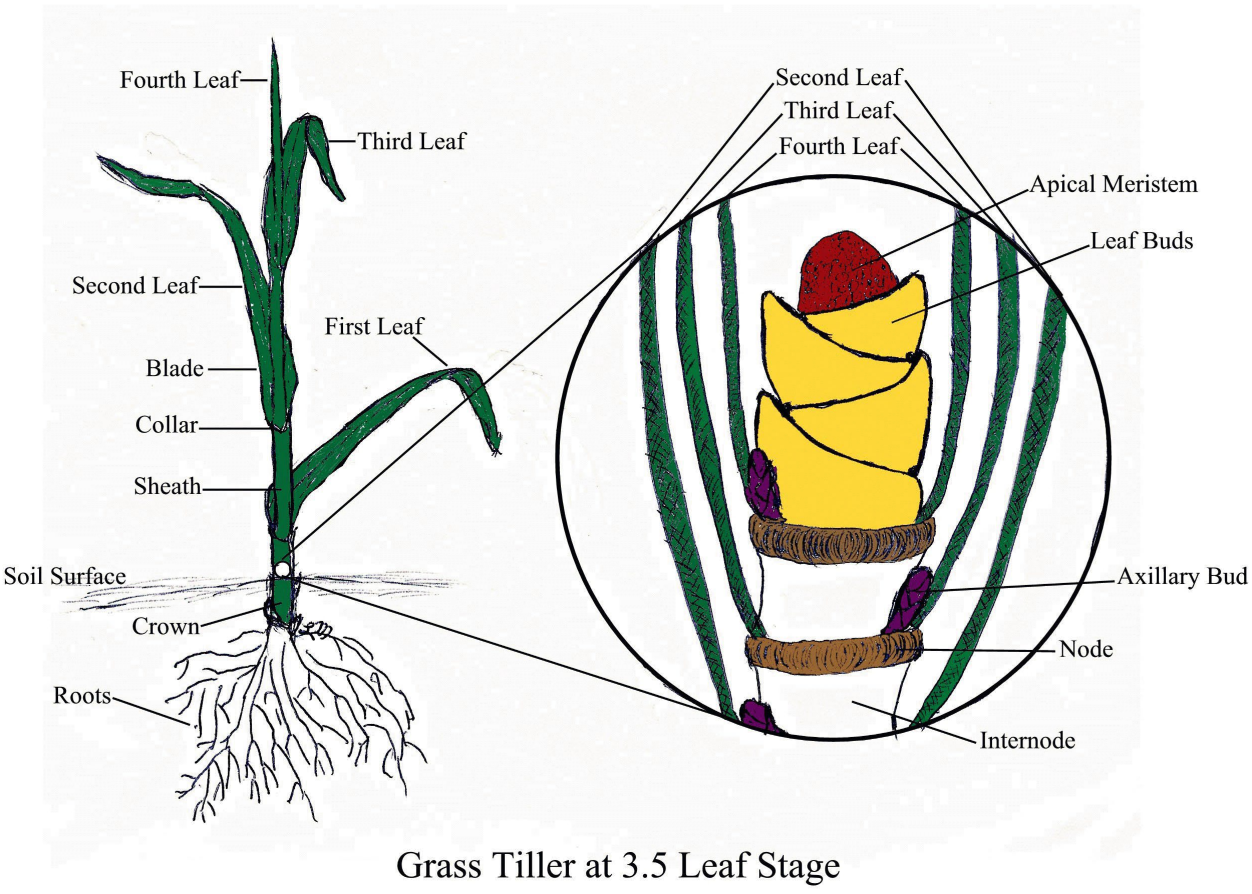

Figure 10. Grass Tiller Structures.

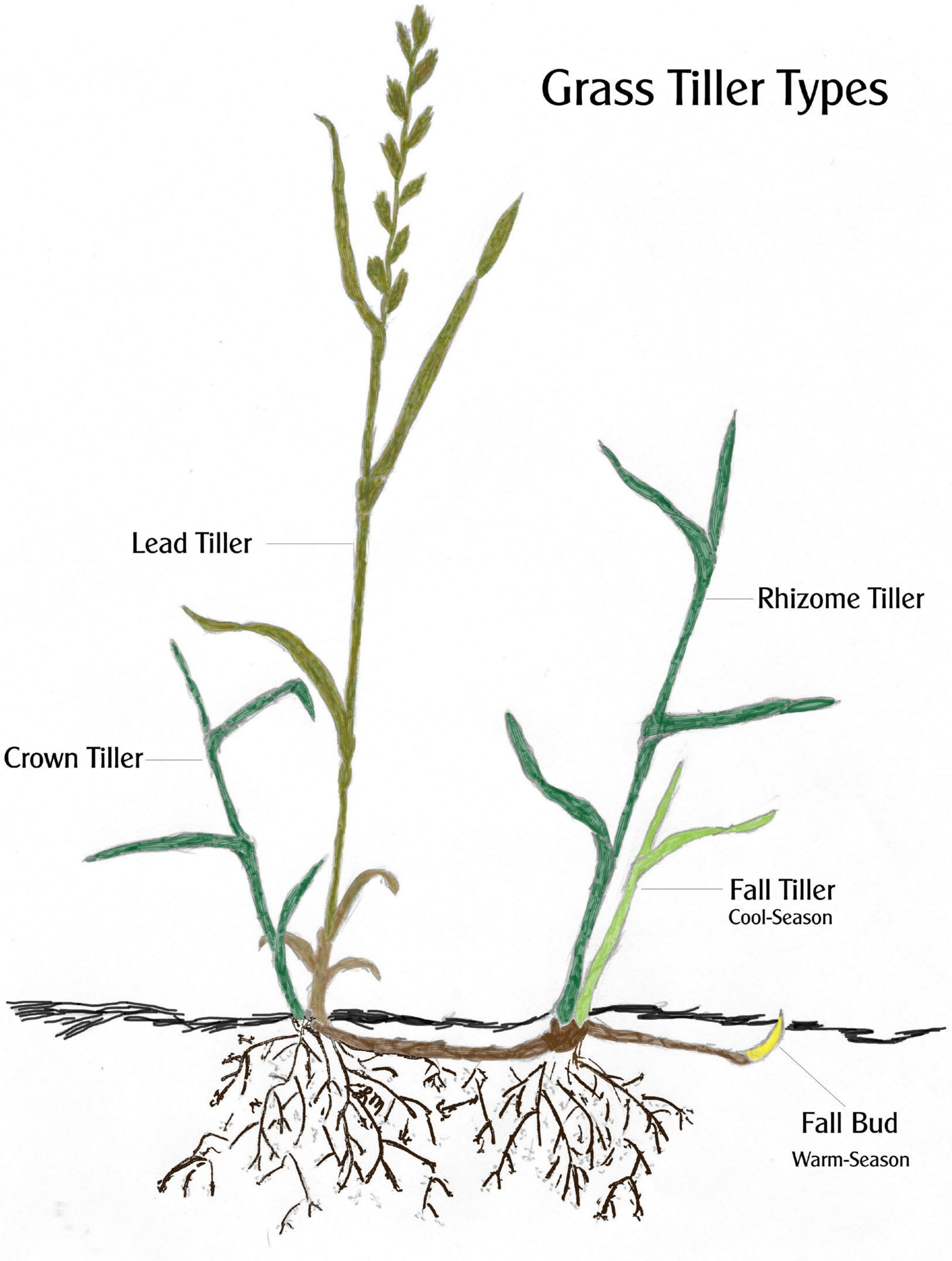

Figure 11. Vegetative Reproduction by Tillering.

Table 2. Traditional management Spring, Summer, and Fall grazing periods, stocking rates, and pasture costs.

Traditional Management	Grazing Period	# Days	# Months	Acres per C-Cpr	Acres per AUM	Pasture Cost $	Cost per day $
Spring	4 May-1 Jun	28	0.92	2.14	2.33	18.75	0.67
Summer	1 Jun-14 Oct	135	4.43	11.43	2.58	100.13	0.74
Fall	14 Oct-13 Nov	30	0.98	4.04	4.11	35.39	1.18
Season	4 May-13 Nov	193	6.33	17.61	2.78	154.27	0.80

Table 3. Biologically Effective management Spring, Summer, and Fall grazing periods, stocking rates, and pasture costs.

Biologically Effective Management	Grazing Period	# Days	# Months	Acres per C-Cpr	Acres per AUM	Pasture Cost $	Cost per day $
Spring	4 May-1 Jun	28	0.92	1.20	1.30	10.51	0.38
Summer	1 Jun-14 Oct	135	4.43	10.22	2.26	89.53	0.66
Fall	14 Oct-13 Nov	30	0.98	1.39	1.41	12.18	0.41
Season	4 May-13 Nov	193	6.33	12.81	2.02	112.22	0.58

Table 4. Traditional management Spring, Summer, and Fall cow and calf weight performance and net returns.

Traditional Management	Gain per Head lbs	Gain per Day lbs	Gain per Acre lbs	Pasture Weight Gain/Value $	Net Return per C-Cpr $	Net Return per Acre $	Cost/lb Calf Gain $
Spring							
Calf	72.67	2.57	32.93	50.87	32.12	15.00	0.26
Cow	59.15	2.05	26.67				
Summer							
Calf	354.37	2.65	30.61	248.06	147.93	12.94	0.28
Cow	67.11	0.50	5.91				
Fall							
Calf	17.73	0.59	4.38	12.41	-22.98	-5.69	1.99
Cow	-52.20	-1.74	-12.90				
Season							
Calf	444.77	2.30	25.26	311.34	157.07	8.92	0.35
Cow	74.06	0.38	4.21				

Table 5. Biologically Effective management Spring, Summer, and Fall cow and calf weight performance and net returns.

Biologically Effective Management	Gain per Head lbs	Gain per Day lbs	Gain per Acre lbs	Pasture Weight Gain/Value $	Net Return per C-Cpr $	Net Return per Acre $	Cost/lb Calf Gain $
Spring							
Calf	76.45	2.61	66.60	53.52	43.00	35.84	0.14
Cow	75.43	2.60	65.49				
Summer							
Calf	380.47	2.89	37.66	266.33	176.80	17.30	0.24
Cow	86.92	0.66	8.68				
Fall							
Calf	50.34	1.82	37.12	35.24	23.06	16.59	0.24
Cow	42.60	1.62	32.22				
Season							
Calf	507.26	2.63	39.88	355.19	242.86	18.96	0.22
Cow	204.95	1.06	16.11				

Table 6. Traditional management Spring, Summer, and Fall mean monthly herbage biomass (lbs/ac).

Seasonality	Apr	E May	L May	Jun	Jul	Aug	Sep	Oct	Nov
Spring	546	1261	797	1018	1182	1102	1019		
Summer				642	851	802	771	784	
Fall								891	668

Table 7. Biologically Effective management Spring, Summer, and Fall mean monthly herbage biomass (lbs/ac).

Seasonality	Apr	E May	L May	Jun	Jul	Aug	Sep	Oct	Nov
Spring	1330	2183	1039	1363	1797	1734	1764		
Summer				855	1065	1003	1128	1001	
Fall				1689	2211	2292	3022	3141	1496

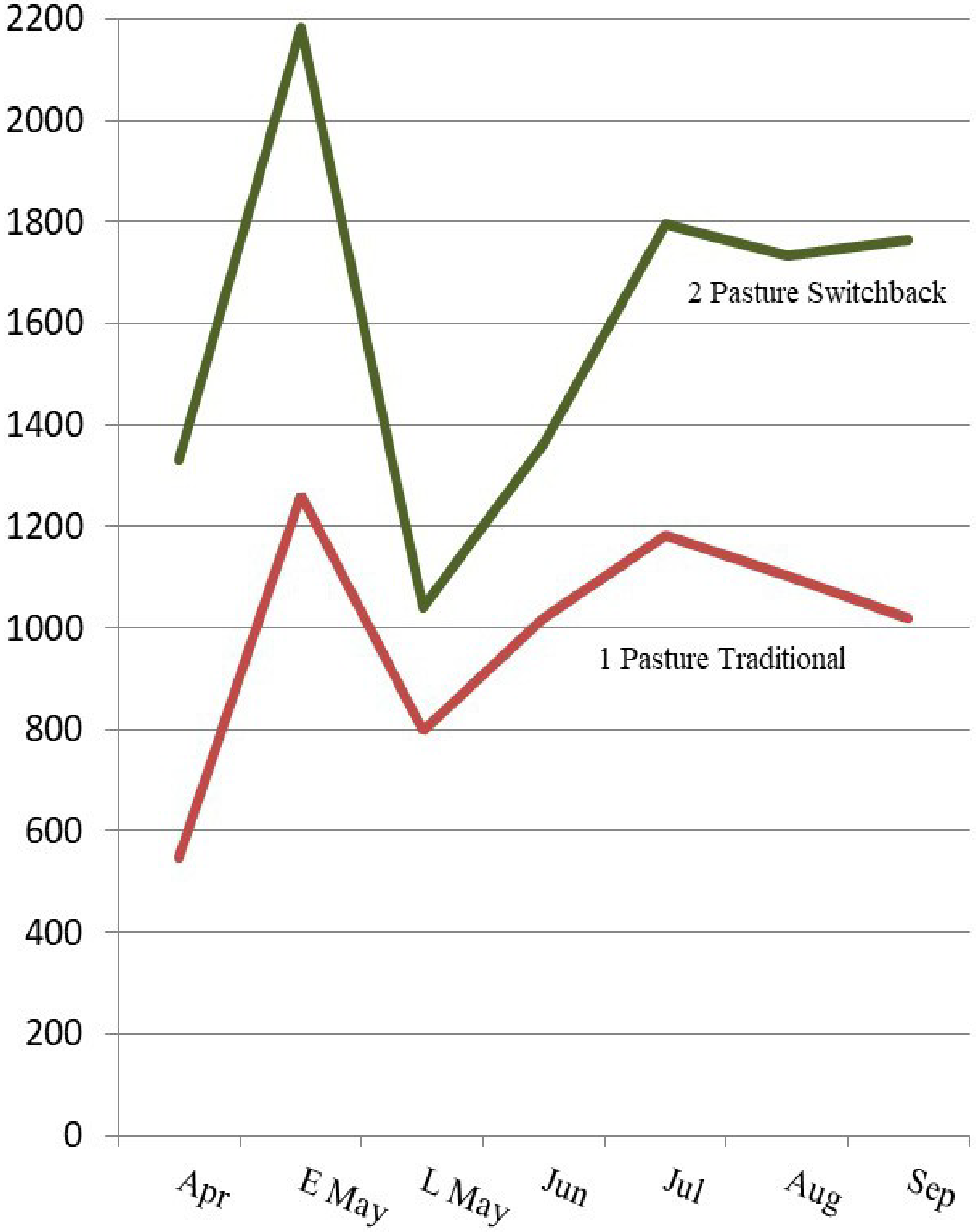

Figure 12. Mean monthly crested wheatgrass biomass (lbs/ac) on 1 Pasture Traditional and 2 Pasture Switchback management strategies.

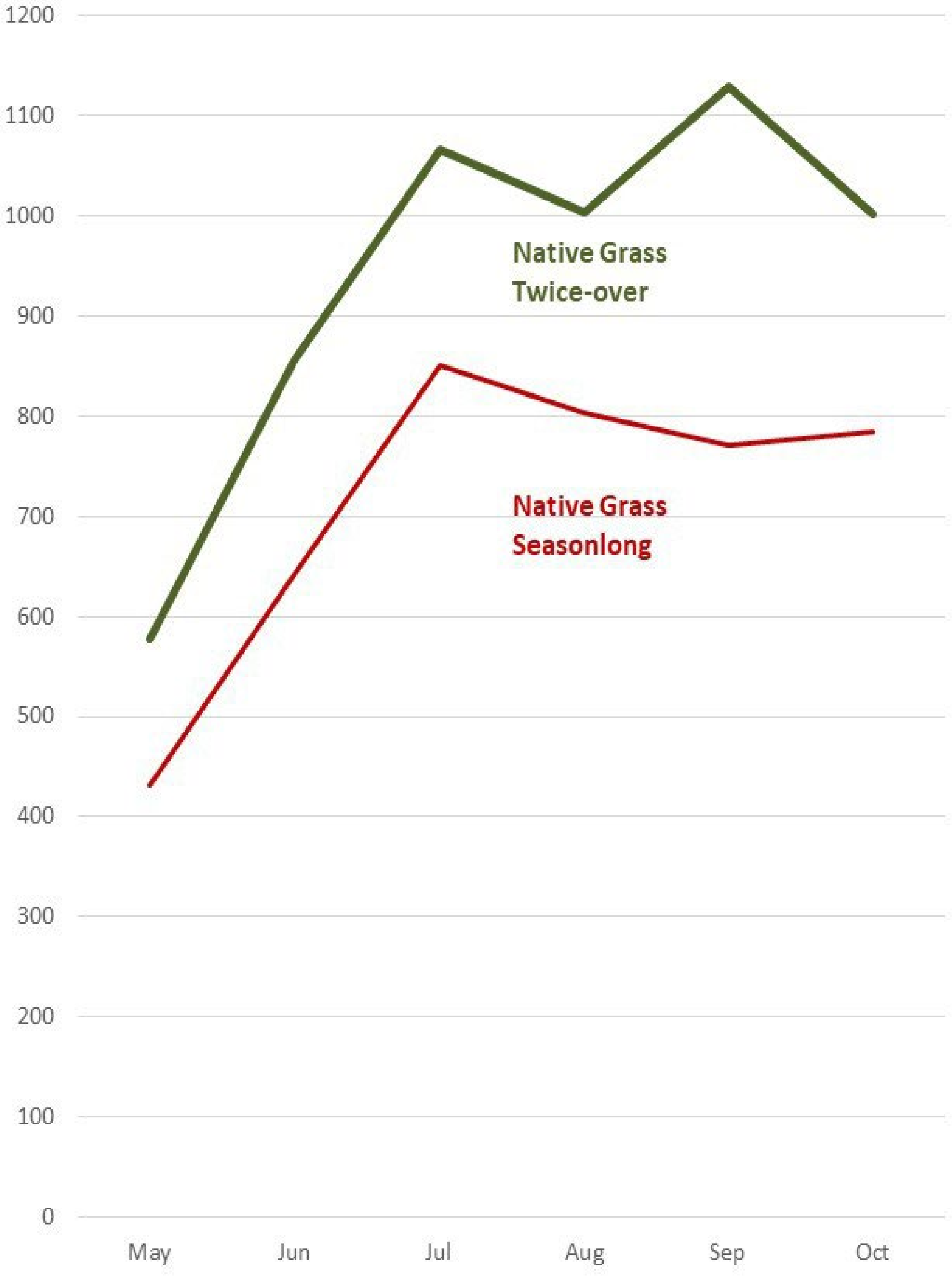

Figure 13. Mean monthly native grass biomass (lbs/ac) on seasonlong and twice-over management strategies.

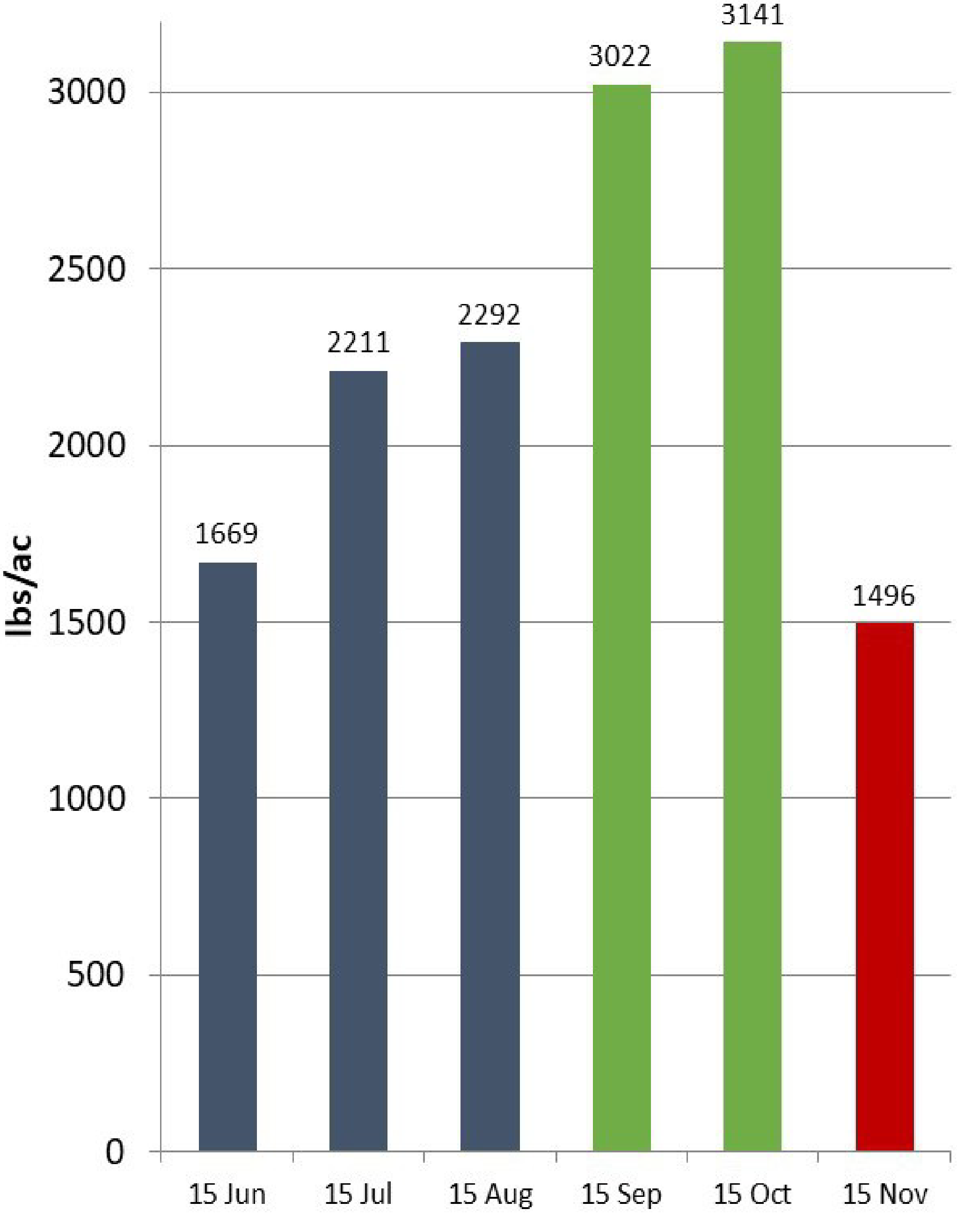

Figure 14. Altai wildrye mean monthly herbage biomass (lbs/ac) on two pastures fall grazed during mid October to mid November, 1984-2002.

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Agricultural lands have the potential to reduce the rate of Global Warming

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Managers of agricultural land are on the cusp of being able to greatly assist the world by helping to reduce the rate of global warming while the world population makes changes to reduce greenhouse gas emissions. The global mean temperature has increased since 1750, which has been designated as the start of the industrial revolution. However, mean global temperatures have been measured only since 1880. Between 1880 and 2020, the mean global temperature has increased about 1.2 C (2.16 F) (Rosen 2021). Global warming has been determined to not be caused by increased solar energy, changes in ocean circulation, or changes in volcanic activity. Global warming is caused by the increased emissions of greenhouse gases into the atmosphere that are byproducts from increased burning of fossil fuels during the period of the industrial revolution (Rosen 2021). The three primary greenhouse gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The rate of global warming increase has recently been found to be slower than expected because of agricultural land's ability to capture and store greenhouse gases (Schimel et al. 2015, Keenan and Williams 2018).

Pastureland and cropland soils annually capture and store some of the greenhouse gases now, however, these soils have the potential to greatly increase the quantity of soil stored greenhouse gases, and also increase production levels, when agricultural lands are managed to enhance the ecosystem processes that capture and store greenhouse gases in soils. Forestlands have been considered to be the worlds guardian ecosystems because they can store greenhouse gases in both the soils and in the unharvested wood of the long-lived trees. The carbon in wood of living trees is protected from decomposition and respiration. However, the stored greenhouse gases in wood have only a limited period of a few hundred years of storage after the wood is harvested as lumber, the exposed wood slowly decomposes and releases the greenhouse gases into the atmosphere. Properly managed soils of pastureland and rejuvenated cropland have the potential to store greater quantities of greenhouse gases than forest soils because forestlands are managed for tree harvest but the soils are not managed unless they are also grazed.

The earth systems of atmosphere (air), lithosphere (rigid crust on tectonic plates), geosphere (rock and mineral), pedosphere (soil), hydrosphere (water), cryosphere (frozen water), and biosphere (living organisms) are fully integrated and have complex overlaping interactions. These interactive processes of the earth systems maintained a relatively constant global temperature since the end of the last ice age for 10,000 years during the Holocene epoch (FAO 2017). During this stable climate period, the greenhouse gases remained at about the same abundance quantities in the atmosphere; carbon dioxide (CO_2) stayed at 260-300 ppm, methane (CH_4) stayed at 700 ppb, and nitrous oxide (N_2O) stayed at 180-260 ppb (Working Group I 2007).

The earth's atmosphere is separated into five layers. The Troposphere is the densest lower layer from earth's surface to 14 km (9 mi). The composition of this lower layer is fairly constant up to a height of 10 km, 33,000 ft, 6.25 mi. It contains 78.084 % nitrogen gas (N_2), 20.946% oxygen gas (O_2), and 0.936% inert gases. The greenhouse gas content is 0.0412% carbon dioxide (CO_2), 0.000187% methane (CH_4), a very small % nitrous oxide (N_2O), and about 3% water vapor (H_2O) which is almost all of the atmospheric water vapor. The Stratosphere extends from 14 to 50 km (9 to 31 mi). Most commercial airplanes fly in the lower portion of this layer. This layer contains the beneficial ozone layer that protects life on earth from the sun's harmful high energy UV radiation. The Mesosphere extends from 50 to 85 km (31 to 53 mi). It has the earth's coldest temperatures at the top of this layer (-90 C, -130 F). Most meteors burnup in this layer. The Thermosphere extends from 85 to 600 km (53 to 372 mi). This layer is where the aurora (northern and southern lights) occurs, it is water vapor and cloud free, and is the lowest layer of the ionosphere that reflect radio waves and absorbs x-rays and UV radiation. The Exosphere is the highest layer that extends from 600 to 10,000 km (372 to 6,200 mi). This is where the atmosphere meets outer space. Light gases like hydrogen that reach this layer can escape into space. Our numerous satellites orbit in this layer (Anonymous 2021e).

These five atmospheric layers remain in place around the earth because of earth's gravity. Viewed from earth, the atmosphere appears to be thick reaching 10,000 km or 6,200 miles in height. However, viewed from space, the earth's atmosphere appears to be very thin and fragile requiring special care.

The Lithosphere is the essential rigid supporting crust of solid land and upper mantle on the earth's surface that has been separated into 15 major moveable tectonic plates that are the foundation for the oceonic and terrestrial habitats. If earth were a gaseous planet, there would be no solid place for a biosphere to form. The Geosphere is the abiotic rock, regolith, and mineral portion of the earth's surface and are the source material during pedogenesis (soil formation) (Anonymous 2021d).

The Pedosphere is the outermost layer of soil on the earth located at the interface of the lithosphere, atmosphere, hydrosphere, and biosphere. It consists of gases, minerals, liquids, and biologic components and is the foundation for terrestrial life on earth (Anonymous 2021c).

The Hydrosphere is the earth's water that has a total volume of 1.386 billion cubic kilometers (333 million cubic miles) (Anonymous 2021b). The earth's water is located in several reservoirs (table 1) with 96.5% of the water in the oceans and 3.5% located in terrestrial reservoirs and only 2.5% of the earth's water is fresh. Earth's water is in continuous cyclical movement above and below the surface under the force of gravity or gravity induced pressures from higher to lower elevation that eventually reaches the oceans. Energy from the sun drives the water cycle that transforms liquid water into a gas (table 2) with 83.2% of the earth's water vapor coming from the oceans and 16.8% coming from terrestrial sources. Water vapor is the most abundant greenhouse gas with a variable weight of roughly 1.29 E kg (E=Exa quintillion 10^{18}kg) which reflects some of the solar energy back to space and reradiates some of the longwave radiation back to earth (Anonymous 2021e). Water vapor is less dense than the major atmospheric components of nitrogen and oxygen gas causing water vapor to rise in altitude until it reaches cooler air and condenses into tiny water droplets that are visible as clouds. On average clouds cover 60% of the earth (Working Group I 2007). Atmospheric circulation moves these clouds around the globe. The tiny cloud droplets condense around small aerosol particles floating in the atmosphere and form rain drops heavy enough to fall to earth (Jacob and Winner 2009, von Schneidemesser et al. 2015). Global precipitation occurs 78% over the oceans, 21% over land, and 1% as snow (Anonymous 2021a). The portion of global precipitation that falls on land, about 35% of the water moves to groundwater or becomes water runoff that moves rapidly to the oceans. The rest of the terrestrial precipitation returns to the atmosphere by evapotranspiration, with 64% as transpiration from plants, 27% is intercepted by plant leaves and later evaporates, 6% evaporates from soils, and 3% of the water that infiltrates soils moves underground to surface water and then evaporates (Rojas-Burke 2015) (table 2).

Water has various residence time in the earth's water reservoirs (table 3) with water spending thousands of years as ice, in the oceans, and as deep groundwater, water can spend hundreds of years as shallow groundwater or in deep lakes, and can spend weeks to months as soil water, snow cover, or moving in a river. Atmospheric water vapor spends an average of 8.9 ± 0.4 days before falling as precipitation (van der Ent and Tuinenburg 2017). Biological water is the small amount of only 0.000081% of the earth's water contained in all living organisms (table 1) and has a short residence time of only 7 days (table 3).

The Cryosphere is the frozen water on the earth. It is an important component of the earth's climate system because the cryosphere reflects about 10% of the suns energy back to space that helps maintain the earths global temperature. As the earth's climate warms and ice melts, the quantity of the suns energy reflected to space is reduced and the increased solar energy that is absorbed increases the global temperature. Increased quantities of melted ice raise the level of the ocean's and the addition of fresh water to the oceans changes the circulation of the worlds ocean currents. Ice melting can change from solid water to liquid water or by sublimation pass directly to water vapor (Working Group I 2007).

The Biosphere includes all of the earth's living organisms associated with soil, ocean, or atmosphere from blue whales to mosquitoes, and from redwood trees to lichens. Living organisms generally contain about 50% to 75% water with a combined total of 0.003% of the earth's fresh water. The earth's fresh water is an extremely small proportion of only 2.5% of total amount of water. Of the earth's fresh water, 69.6% is frozen, 30.1% is groundwater, only 0.3% is in lakes and rivers, 0.05%

is in soil, and 0.04% is in the atmosphere as water vapor (Anonymous 2021b).

Energy from the sun drives the earth's climate. The sun radiates energy at very short wavelengths at the visible and near visible (ultraviolet) part of the electromagnetic spectrum. The solar energy reaching the earth's atmosphere that is facing the sun is about 1,365 Watts m^{-2} (Working Group I 2007) with greater amounts at the equator than at the north and south latitudes. About 20% of this energy is reflected back to space by clouds and small aerosol particles, and about 10% of this energy is reflected by the earth's cryosphere, the ice, snow, and glaciers. Collectively, this high reflectivity is called the earth's albedo. The suns energy not reflected back to space is absorbed by the atmosphere at about 78 W m^{-2} of latent heat, and is absorbed by the earth's surface as heat at about 168 to 240 W m^{-2} (Working Group I 2007). In order to balance the incoming solar radiation, the earth emits the same amount of energy as outgoing longwave radiation. If all of this longwave energy were permitted to escape into space, the average global temperature of the earth would be -19 C (-2.2 F) (Working Group I 2007) and all water would be frozen and no life could exist. Fortunately, the earth is protected by a partial blanket known as the natural greenhouse effect made up of atmospheric water vapor as clouds and carbon dioxide that absorbs and reradiates some of the earth's longwave radiation back to the earth resulting in a normal average earth temperature of around 14 C (57 F) (Working Group I 2007) in which some water is liquid and life as we know can exist. These complex interactions of the earth's systems maintained a stable global temperature for 10,000 years.

Over thousands of years, humans developed and greatly improved agricultural practices that provided adequate nutrition for an increasing global population that developed complex civilizations that in a short time required mass production of goods from factories which at first were powered by water. Soon to be followed by the inventions of the steam engine and combustion engine that powered the industrial revolution from compressed deposits of fossil dead and decayed organic matter that had formed into coal, oil, and natural gas that contained huge quantities of low cost energy.

At the start of the industrial revolution, scientists could not measure atmospheric changes. The thermometer was invented in the early 1600's but coordinated meteorological data were not collected until the mid 1850's. Standardized meteorological observations were collected at more than 100 world stations by 1880's (Working Group I 2007). The concept that atmospheric gases create a greenhouse effect was developed over a 250 year period with initial idea started in 1681, advanced in 1760, 1824, 1859, 1895, and then the equations that linked greenhouse gases and climate change were solved in 1938 by G.S. Callendar. High accuracy measurements of atmospheric CO_2 was initiated in 1958 and documented changes in the composition of the atmosphere were made in 1961 and 1998 by Keeling (Working Group I 2007). Long term change in the composition of the worlds air came from analysis of firn bubbles in ice cores from Greenland and Antarctica during the 1980's and 1990's.

During the 1950's to 1970's, greenhouse gas warming was strongly concerned to be caused by carbon dioxide CO_2, water vapor H_2O, methane CH_4, nitrous oxide N_2O, and chlorofluorocarbons CFC which were several synthetic halocarbons. During the 1990's, advanced computer programs determined that anthropogenic activity caused climate change by the greenhouse gas effect through an increase in the quantity of atmospheric carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Walker and Steffen 1997, Working Group I 2007).

Atmospheric carbon dioxide quantity has increased from 280 ppm to 412 ppm over a 270 year period from fossil fuel burning and cement production during the industrial revolution and has increased the global temperature 1.2 C (2.16 F) by retaining greater quantities of solar energy on earth. Global warming increases water evaporation from oceans, the warmer atmosphere holds greater quantities of water vapor, resulting in increased global precipitation, which is not evenly distributed. The warmer atmosphere also increases natural deposition of nitrogen (primarily as NO_2 with a residence time of hours to days), which also is not evenly distributed. Increases in atmospheric carbon dioxide enhance plant photosynthetic processes that remove increased quantities of carbon dioxide from the atmosphere, called the CO_2 effect (Matthews et al. 2005, Govind and Kumari 2014, Schimel et al. 2015). As the quantity of fixed carbon (carboxylation) increases, the amount of nitrogen used in assimilation of organic matter also increases, resulting in increased plant growth with greater biomass (Zaehle 2013). These increases in water, energy, carbon, and nitrogen increase ecosystem productivity and increases the allocation of photosynthate to the roots that increase the quantity of soil organic matter (SOM) with greater amounts of carbon (SOC) put into storage in the soils (Schimel et al. 1997, Walker and Steffen 1997). Increases in soil carbon improve nutrient storage, increase water holding capacity, and enhance aggregation.

Long term persistence of carbon storage in soils by the most promising biogeochemical processes requires a large active microorganism biomass. Carbon sequestration of decomposed stabilized organic matter in terrestrial soils must have microbial action for mineral surface binding within microaggragates which reduces exposure of the carbon to enzymatic degradation (FAO and ITPS 2015). A substantial increase in terrestrial soil sequestration of atmospheric carbon dioxide can be as effective at reducing the rate of global warming as the primary objective to reduce emissions of carbon dioxide from fossil fuel burning (FAO 2017).

All living organisms release carbon dioxide during respiration. Autotrophic plants use inorganic material for their production and energy source and release a portion of the intake as carbon dioxide during respiration. Heterotrophic animals use organic material for their production and energy source and release a portion of the intake as carbon dioxide during respiration. If the quantity of carbon in respiration is about equal to the carbon used in production, that organism is near equilibrium (Keenan and Williams 2018). Projection of this analogy, equilibrium of carbon use and release, could work for an ecosystem or the world. The quantity of atmospheric carbon dioxide remained at nearly the same level for 10,000 years before the industrial revolution; the carbon used in production and the quantity of carbon released during respiration were near equilibrium.

Carbon dioxide emissions from terrestrial soils that are derived from organic matter decomposition, exudation by plant roots, and microbial respiration are at about the same amount as the annual net primary production of carbon in the growing biomass, near equilibrium. The total carbon dioxide emissions from terrestrial soils is about ten times greater than the total amount of carbon dioxide emissions into the atmosphere by all fossil fuel burning (Schimel 1995).

Terrestrial soils have stored a huge quantity of carbon at a level of 1417 Pg of SOC to a 1 meter depth (Pg=Peta quadrillion 10^{15}g) (Hiederer and Kochy 2011, FAO and ITPS 2015). The terrestrial soil carbon storage is large and has been increasing because the increase of atmospheric carbon dioxide has increased terrestrial plant photosynthetic rates and plant growth biomass. During the eighteen year period of 1990 to 2007, terrestrial soil carbon storage increased at a rate of 2.5 Pg C yr^{-1} (Schimel et al. 2015). During the eleven year period of 2007 to 2017, terrestrial soil carbon storage increased at a rate of 3.61 Pg C yr^{-1} (Keenan and Williams 2018). These increases in soil carbon storage mean that, with the CO_2 effect, terrestrial soils are removing CO_2 from the atmosphere at a rate equivalent to all of the CO_2 emissions from the soils plus about 33.7% of the CO_2 emissions from all the fossil fuel burning per year. This is the reason, the rate of global warming is increasing at a rate slower than expected (Schimel et al 2015, Keenan and Williams 2018).

The carbon storage in the oceans is important but has not changed much. During 1990 to 2007, oceanic carbon storage was at 2.3 Pg C yr^{-1} (Schimel et al. 2015). During 2007 to 2017, oceanic carbon storage was at 2.36 Pg C yr^{-1} (Keenan and Williams 2018).

The total annual anthropogenic (human caused) carbon dioxide emissions increased during the decade of 2007 to 2017 compared to an earlier 18 year period of 1990 to 2007. During 2007 to 2017, total annual carbon dioxide emissions were 10.68 Pg yr^{-1}, an increase of 9.0%, emissions from fossil fuel burning increased 35.4%, from cement production increased 37.1%, and from tropical deforestation decreased 54.1% compared to the earlier period. The quantity of atmospheric carbon dioxide increased to 4.71 Pg yr^{-1} which was only 44.1% of the total annual carbon dioxide emissions. The annual rate of carbon dioxide emissions added to the atmosphere did not increase as much as expected because the annual amount of carbon dioxide that was moved into terrestrial soils increased 44.4% compared to the earlier period as a result of the CO_2 effect that increased plant photosynthesis (Schimel et al. 2015, Keenan and Williams 2018). The annual amount of carbon dioxide removed by the oceans changed very little with an increase of 2.6%. The combined quantity of atmospheric carbon dioxide removed by the terrestrial soils and oceans increased 47% compared to the earlier period.

Methane (CH_4) emissions are produced by methanogenesis when decomposition of organic matter occurs under anaerobic conditions (without oxygen) in waterlogged soils. The total methane production in the world is at 145 Tg yr^{-1} (Tg=tera trillion 10^{12}g), with 92 Tg $yr^{-1}$from natural wetlands and peatlands and 53 Tg yr^{-1} from rice fields. Research to reduce methane production in rice fields is being conducted and has developed effective results. Some additional methane is emitted from landfills, biomass burning, and domestic sewage. Methane has an atmospheric residence time of about 10 years. In the atmosphere, methane is eliminated by reacting with hydroxyl radicals (OH). In undisturbed aerobic upland soils of grasslands and forestlands, about 10% of methane emissions are eliminated through microbial oxidation (methanotrophy) (FAO and ITPS 2015).

Nitrous oxide (N_2O) emissions are produced by industrial fossil fuel burning and biomass burning at about 12 Tg yr^{-1} and from agricultural cropland emissions at just over 4 Tg yr^{-1} caused by application of greater quantities of nitrogen fertilizer than needed by the plants. The total atmospheric nitrous oxide emissions are at about 16 Tg yr^{-1} for the world. Emissions of nitrous oxide from cropland soils occurs when surplus fertilizer nitrogen converts to nitrous oxide gas. Nitrous oxide emissions from agricultural soils can be reduced by decreasing the quantity of nitrogen inputs or by matching application time and amount with plant demand which would greatly improve plant nitrogen use efficiency (FAO and ITPS 2015).

Carbon dioxide, methane, and nitrous oxide emissions are still being added to the earth's atmosphere and the climate is still warming, albeit, at a slower rate then expected. The worlds forestlands are removing about as much carbon dioxide as they can. However, the worlds cropland and pastureland soils have the potential to remove much more atmospheric carbon dioxide than they are at the present.

The worlds forest soils plus the wood in long lived trees hold about 702.0 Pg of SOC which is about 49.6% of the worlds sequestered carbon. Forests occupy around 27.7% of the worlds land area. Many emerging countries, primarily in South America and Asia, have used these vast forestlands for their needed economic development, as a result about 3.3 million km^2 (1.3 million mi^2) of dense tropical forests have been deforested and in the process, the world has lost about 25% of the stored carbon. Fortunately, over the past decade, the rate of deforestation has been reduced, and in conjunction, the rate of afforestation (planting trees) has increased and the amount of forestland designated for conservation of biological diversity has also increased (FAO and ITPS 2015).

The development of agriculture has permitted the development of an advanced human civilization. The estimated historical progression of the amount of the worlds land area occupied by cropland has been 1%, 2%, and 12.6% during the years of 1000, 1700, and 2005, respectively (FAO and ITPS 2015). Increases in the amount of cropland area required the conversion of natural forest and grassland ecosystems which has caused great losses of stored soil carbon at quantities of 40 to 90 Pg of SOC. The rate of re-carbonization of agricultural managed cropland is slow. Collectively, all cropland soils to 1 meter depth hold only 160.2 Pg of SOC which is about 11.3% of the worlds sequestered carbon (FAO and ITPS 2015). Cropland soils are low in SOC which indicates deficiencies in organic matter, nutrients, and microbial biomass. Cropland soils are biologically and ecologically degraded requiring huge organic inputs much greater than the quantity recommended to reduce wind and water erosion. A large microorganism biomass is needed to perform vital biogeochemical processes and to remove greater quantities of carbon dioxide from the atmosphere.

Pasturelands, which include rangelands, grasslands, shrublands, and seeded herbaceous lands, occupy around 23.8% of the worlds land area. Pastureland soils hold 438.7 Pg of SOC to 1 meter depth which is about 31.0% of the worlds sequestered carbon (FAO and ITPS 2015). Most pasturelands are managed by unsophisticated grazing practices based on traditional aboveground plant stewardship that does not address grass growth mechanism requirements nor ecosystem biogeochemical processes. As a consequence, pasturelands are deficient in the quantity of available mineral nitrogen resulting in reduced grass production that has inadequate nutrient content after mid to late July causing low calf weight gains. Even though, pastureland soils hold relatively large quantities of sequestered carbon, they have the potential to capture and store larger quantities of atmospheric carbon dioxide, if they had better ecological management (Manske 2018) (https://hdl.handle.net/10365/28801).

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Table 1. Distribution of Water on Earth.

Source	Volume km^3	Volume mi^3	% Total Water
Total Water	1,386,000,000	332,519,084	
Oceans	1,338,000,000	321,003,272	96.54
Frozen Water	24,364,000	5,845,234	1.76
Groundwater, Saline	12,870,000	3,087,677	0.93
Groundwater, Fresh	10,530,000	2,526,281	0.76
Lake, Saline	85,400	20,489	0.0062
Lake, Fresh	91,000	21,832	0.0066
Swamp	11,470	2,752	0.00083
River	2,120	509	0.00015
Soil Water	16,500	3,959	0.0012
Atmosphere	12,900	3,095	0.00093
Biological Water	1,120	269	0.000081

Data from Anonymous 2021b.

Table 2. Evaporation to Water Vapor per year on Earth.

Source	Volume km^3	Volume mi^3	% Total Water Vapor
Total Water Vapor	505,000	121,156	
Ocean	420,000	100,763	83.2
Terrestrial	85,000	20,393	16.8
Plant Transpiration	55,000	13,195	10.9
Plant Interception	23,000	5,518	4.6
Soil Water	5,000	1,200	1.0
Surface Water	2,000	480	0.4

Data from Rojas-Burke 2015 and Anonymous 2021a.

Table 3. Residence Time of Water on Earth.

Source	Period of Time
Polar Ice	20,000 to 800,000 yrs
Glaciers	100 to 10,000 yrs
Oceans	3,200 to 4,000 yrs
Groundwater deep	10,000 yrs
Groundwater shallow	2 wks to 200 yrs
Lake	10 to 100 yrs
Swamp	1 to 10 yrs
Soil Water	2 wks to 1 yr
Snow cover	2 to 6 mo
River	2 wks to 6 mo
Atmosphere	8 to 11 days 8.9 days
Biological water	7 days

Data from Anonymous 2021a.

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Range Plant Growth Related to Climatic Factors of Western North Dakota, 1982-2021.

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Introduction

Successful long-term management of grassland ecosystems requires knowledge of the relationships of range plant growth and regional climatic factors. Range plant growth and development are regulated by climatic conditions. Length of daylight, temperature, precipitation, and water deficiency are the most important climatic factors that affect rangeland plants (Manske 2011).

Light

Light is necessary for plant growth because light is the source of energy for photosynthesis. Plant growth is affected by variations in quality, intensity, and duration of light. The quality of light (wavelength) varies from region to region, but the quality of sunlight does not vary enough in a given region to have an important differential effect on the rate of photosynthesis. However, the intensity (measurable energy) and duration (length of day) of sunlight change with the seasons and affect plant growth. Light intensity varies greatly with the season and with the time of day because of changes in the angle of incidence of the sun's rays and the distance light travels through the atmosphere. Light intensity also varies with the amount of humidity and cloud cover because atmospheric moisture absorbs and scatters light rays.

The greatest variation in intensity of light received by range plants results from the various degrees of shading from other plants. Most range plants require full sunlight or very high levels of sunlight for best growth. Shading from other plants reduces the intensity of light that reaches the lower leaves of an individual plant. Grass leaves grown under shaded conditions become longer but narrower, thinner (Langer 1972, Weier et al. 1974), and lower in weight than leaves in sunlight (Langer 1972). Shaded leaves have a reduced rate of photosynthesis, which decreases the carbohydrate supply and causes a reduction in growth rate of leaves and roots (Langer 1972). Shading increases the rate of senescence in lower, older leaves. Accumulation of standing dead leaves ties up carbon and nitrogen. Decomposition of leaf material through microbial activity can take place only after the leaves have made contact with the soil. Standing dead material not in contact with the soil does not decompose but breaks down slowly as a result of leaching and weathering. Under ungrazed treatments the dead leaves remain standing for several years, slowing nutrient cycles, restricting nutrient supply, and reducing soil microorganism activity in the top 12 inches of soil. Standing dead leaves shade early leaf growth in spring and therefore slow the rate of growth and reduce leaf area. Long-term effects of shading, such as that occurring in ungrazed grasslands and under shrubs or leafy spurge, reduce the native grass species composition and increase composition of shade-tolerant or shade-adapted replacement species like smooth bromegrass and Kentucky bluegrass.

Day-length period (photoperiod) is one of the most dependable cues by which plants time their activities in temperate zones. Day-length period for a given date and locality remains the same from year to year. Changes in the photoperiod function as the timer or trigger that activates or stops physiological processes bringing about growth and flowering of plants and that starts the process of hardening for resistance to low temperatures in fall and winter. Sensory receptors, specially pigmented areas in the buds or leaves of a plant, detect day length and night length and can activate one or more hormone and enzyme systems that bring about physiological responses (Odum 1971, Daubenmire 1974, Barbour et al. 1987).

The phenological development of rangeland plants is triggered by changes in the length of daylight. Vegetative growth is triggered by photoperiod and temperature (Langer 1972, Dahl 1995), and reproductive initiation is triggered primarily by photoperiod (Roberts 1939, Langer 1972, Leopold and Kriedemann 1975, Dahl 1995) but can be slightly modified by temperature and precipitation (McMillan 1957, Leopold and Kriedemann 1975, Dahl and Hyder 1977, Dahl 1995). Some plants are long-day plants and others are short-day plants. Long-day plants reach the flower phenological stage after exposure to a critical photoperiod and during the period of increasing daylight between mid April and mid June. Generally, most cool-season plants with the C_3 photosynthetic pathway are long-day plants and reach flower phenophase before 21 June. Short-day plants are induced into flowering by day lengths that are shorter than a critical length and that occur during the period of decreasing day length after mid June. Short-day plants are technically responding to the increase in the length of the night period rather than to the decrease in the day length (Weier et al. 1974, Leopold and Kriedemann 1975). Generally, most warm-season plants with the C_4 photosynthetic pathway are short-day plants and reach flower phenophase after 21 June.

The annual pattern in the change in daylight duration follows the seasons and is the same every year for each region. Grassland management strategies based on phenological growth stages of the major grasses can be planned by calendar date after the relationships between phenological stage of growth of the major grasses and time of season have been determined for a region.

Temperature

Temperature is an approximate measurement of the heat energy available from solar radiation. At both low and high levels temperature limits plant growth. Most plant biological activity and growth occur within only a narrow range of temperatures, between 32° F (0 C) and 122° F (50° C) (Coyne et al. 1995). Low temperatures limit biological reactions because water becomes unavailable when it is frozen and because levels of available energy are inadequate. However, respiration and photosynthesis can continue slowly at temperatures well below 32° F if plants are "hardened". High temperatures limit biological reactions because the complex structures of proteins are disrupted or denatured.

Periods with temperatures within the range for optimum plant growth are very limited in western North Dakota. The frost-free period is the number of days between the last day with minimum temperatures below 32° F (0° C) in the spring and the first day with minimum temperatures below 32° F (0° C) in the fall and is approximately the length of the growing season for annually seeded plants. The frost-free period for western North Dakota generally lasts for 120 to 130 days, from mid to late May to mid to late September (Ramirez 1972). Perennial grassland plants are capable of growing for periods longer than the frost-free period, but to continue active growth they require temperatures above the level that freezes water in plant tissue and soil. Many perennial plants begin active growth more than 30 days before the last frost in spring and continue growth after the first frost in fall. The growing season for perennial plants is considered to be between the first 5 consecutive days in spring and the last 5 consecutive days in fall with mean daily temperature at or above 32° F (0° C). In western North Dakota the growing season for perennial plants is considered to be generally from mid April through mid October. Low air temperature during the early and late portions of the growing season greatly limits plant growth rate. High temperatures, high evaporation rates, drying winds, and low precipitation levels after mid summer also limit plant growth.

Different plant species have different optimum temperature ranges. Cool-season plants, which are C_3 photosynthetic pathway plants, have an (10 to 25 C). Warm-season plants, which are C_4 photosynthetic pathway plants, have an optimum (30 to 40 C) (Coyne et al. 1995).

Water (Precipitation)

Water, an integral part of living systems, is ecologically important because it is a major force in shaping climatic patterns and biochemically important because it is a necessary component in physiological processes (Brown 1995). Water is the principal constituent of plant cells, usually composing over 80% of the fresh weight of herbaceous plants. Water is the primary solvent in physiological processes by which gases, minerals, and other materials enter plant cells and by which these materials are translocated to various parts of the plant. Water is the substance in which processes such as photosynthesis and other biochemical reactions occur and a structural component of proteins and nucleic acids. Water is also essential for the maintenance of the rigidity of plant tissue and for cell enlargement and growth in plants (Brown 1977, Brown 1995).

Water Deficiency

Temperature and precipitation act together to affect the physiological and ecological status of range plants. The biological situation of a plant at any time is determined by the balance between rainfall and potential evapotranspiration. The higher the temperature, the greater the rate of evapotranspiration and the greater the need for rainfall to maintain homeostasis. When the amount of rainfall received is less than potential evapotranspiration demand, a water deficiency exists. Evapotranspiration demand is greater than precipitation in the mixed grass and short grass prairie regions. The tall grass prairie region has greater precipitation than evapotranspiration demand. Under water deficiency conditions, plants are unable to absorb adequate water to match the transpiration rate, and plant water stress develops. Range plants have mechanisms that help reduce the damage from water stress, but some degree of reduction in herbage production occurs.

Plant water stress limits growth. Plant water stress develops in plant tissue when the rate of water loss through transpiration exceeds the rate of water absorption by the roots. Water stress can vary in degree from a small decrease in water potential, as in midday wilting on warm, clear days, to the lethal limit of desiccation (Brown 1995).

Early stages of water stress slow shoot and leaf growth. Leaves show signs of wilting, folding, and discoloration. Tillering and new shoot development decrease. Root production may increase. Senescence of older leaves accelerates. Rates of cell wall formation, cell division, and protein synthesis decrease. As water stress increases, enzyme activity declines and the formation of necessary compounds slows or ceases. The stomata begin to close; this reaction results in decreased rates of transpiration and photosynthesis. Rates of respiration and translocation decrease substantially with increases in water stress. When water stress becomes severe, most functions nearly or completely cease and serious damage occurs. Leaf and root mortality induced by water stress progresses from the tips to the crown. The rate of leaf and root mortality increases with increasing stress. Water stress can increase to a point that is lethal, resulting in damage from which the plant cannot recover. Plant death occurs when meristems become so dehydrated that cells cannot maintain cell turgidity and biochemical activity (Brown 1995).

Study Area

The study area is the region around the Dickinson Research Extension Center (DREC) Ranch, Dunn County, western North Dakota, USA. Native vegetation in western North Dakota is the Wheatgrass-Needlegrass Type (Barker and Whitman 1988, Shiflet 1994) of the mixed grass prairie.

The climate of western North Dakota has changed several times during geologic history (Manske 1999). The most recent climate change occurred about 5,000 years ago, to conditions like those of the present, with cycles of wet and dry periods. The wet periods have been cool and humid, with greater amounts of precipitation. A brief wet period occurred around 4,500 years ago. Relatively long periods of wet conditions occurred in the periods between 2,500 and 1,800 years ago and between 1,000 and 700 years ago. Recent short wet periods occurred in the years from 1905 to 1916, 1939 to 1947, and 1962 to 1978. The dry periods have been warmer, with reduced precipitation and recurrent summer droughts. A widespread, long drought period occurred between the years 1270 and 1299, an extremely severe drought occurred from 1863 through 1875, and other more recent drought periods occurred from 1895 to 1902, 1933 to 1938, and 1987 to 1992. The current climatic pattern in western North Dakota is cyclical between wet and dry periods and has existed for the past 5,000 years (Bluemle 1977, Bluemle 1991, Manske 1994a).

Procedures

Daylight duration data for the Dickinson location of latitude 46 48' N, longitude 102 48' W, were tabulated from daily sunrise and sunset time tables compiled by the National Weather Service, Bismarck, North Dakota.

Temperature and precipitation data were taken from historical climatological data collected at the Dickinson Research Extension Center Ranch, latitude 47° 14' N, longitude 102° 50' W, Dunn County, near Manning, North Dakota, 1982-2021.

A technique reported by Emberger et al. (1963) was used to develop water deficiency months data from historical temperature and precipitation data. The water deficiency months data were used to identify months with conditions unfavorable for plant growth. This method plots mean monthly temperature (° C) and monthly precipitation (mm) on the same axis, with the scale of the precipitation data at twice that of the temperature data. The temperature and precipitation data are plotted against an axis of time. The resulting ombrothermic diagram shows general monthly trends and identifies months with conditions unfavorable for plant growth. Water deficiency conditions exist during months when the precipitation data bar drops below the temperature data curve and plants are under water stress. Plants are under temperature stress when the temperature curve drops below the freezing mark (0°C).

Results and Discussion

Light

The tilt of the earth's axis in conjunction with the earth's annual revolution around the sun produces the seasons and changes the length of daylight in temperate zones. Dickinson (figure 1) has nearly uniform day and night lengths (12 hours) during only a few days, near the vernal and autumnal equinoxes, 20 March and 22 September, respectively, when the sun's apparent path crosses the equator as the sun travels north or south, respectively. The shortest day length (8 hours, 23 minutes) occurs at winter solstice, 21 December, when the sun's apparent path is farthest south of the equator. The longest day length (15 hours, 52 minutes) occurs at summer solstice, 21 June, when the sun's apparent path is farthest north of the equator. The length of daylight during the growing season (mid April to mid October) oscillates from about 13 hours in mid April, increasing to nearly 16 hours in mid June, then decreasing to around 11 hours in mid October (figure 1).

Temperature

The DREC Ranch in western North Dakota experiences severe, windy, dry winters with little snow accumulation. The springs are relatively moist in most years, and the summers are often droughty but are interrupted periodically by thunderstorms. The long-term (40-year) mean annual temperature is 42.2º F (5.7º C) (table 1). January is the coldest month, with a mean temperature of 15.0º F (-9.5º C). July and August are the warmest months, with mean temperatures of 69.7º F (20.9º C) and 68.4 F (20.2º C), respectively. Months with mean monthly temperatures below 32.0º F (0.0º C) are too cold for active plant growth. Low temperatures define the growing season for perennial plants, which is generally from mid April to mid October (6.0 months, 183 days). During the other 6 months each year, plants in western North Dakota cannot conduct active plant growth. Soils are frozen to a depth of 3 to 5 feet for a period of 4 months (121 days) (Larson et al. 1968). The early and late portions of the 6-month growing season have very limited plant activity and growth. The period of active plant growth is generally 5.5 months (168 days).

Western North Dakota has large annual and diurnal changes in monthly and daily air temperatures. The range of seasonal variation of average monthly temperatures between the coldest and warmest months is 55.0º F (30.5 C), and temperature extremes in western North Dakota have a range of 161.0º F (89.4º C), from the highest recorded summer temperature of 114.0º F (45.6º C) to the lowest recorded winter temperature of -47.0º F (-43.9º C). The diurnal temperature change is the difference between the minimum and maximum temperatures observed over a 24-hour period. The average diurnal temperature change during winter is 22.0º F (12.2º C), and the change during summer is 30.0º F (16.7º C). The average annual diurnal change in temperature is 26.0º F (14.4º C) (Jensen 1972). The large diurnal change in temperature during the growing season, which has warm days and cool nights, is beneficial for plant growth because of the effect on the photosynthetic process and respiration rates (Leopold and Kriedemann 1975).

Precipitation

The long-term (40-year) annual precipitation for the Dickinson Research Extension Center Ranch in western North Dakota is 17.02 inches (432.40 mm). The long-term mean monthly precipitation is shown in table 1. The growing-season precipitation (April to October) is 14.41 inches (365.83 mm) and is 84.67% of annual precipitation. June has the greatest monthly precipitation, at 3.10 inches (78.69 mm).

The seasonal distribution of precipitation (table 2) shows the greatest amount of precipitation occurring in the spring (7.12 inches, 41.83%) and the least amount occurring in winter (1.61 inches, 9.46%). Total precipitation received for the 5-month period of November through March averages less than 2.61 inches (15.33%). The precipitation received in the 3-month period of May, June, and July accounts for 47.30% of the annual precipitation (8.05 inches).

The annual and growing-season precipitation levels and percent of the long-term mean for 40 years (1982 to 2021) are shown in table 3. Drought conditions exist when precipitation amounts for a month, growing season, or annual period are 75% or less of the long-term mean. Wet conditions exist when precipitation amounts for a month, growing season, or annual period are 125% or greater of the long-term mean. Normal conditions exist when precipitation amounts for a month, growing season, or annual period are greater than 75% and less than 125% of the long-term mean. Between 1982-2021, 5 drought years (12.50%) (table 4) and 8 wet years (20.00%) (table 5) occurred. Annual precipitation amounts at normal levels, occurred during 27 years (67.50%) (table 3). The area experienced 5 drought growing seasons (12.50%) (table 6) and 7 wet growing seasons (17.50%) (table 7). Growing-season precipitation amounts at normal levels occurred during 28 years (70.00%) (table 3). The 6-yearperiod (1987-1992) was a long period with near-drought conditions. The average annual precipitation for these 6 years was 12.12 inches (307.89 mm), only 71.21% of the long-term mean. The average growing-season precipitation for the 6-yearperiod was 9.97 inches (253.11 mm), only 69.19% of the long-term mean (table 3).

Water Deficiency

Monthly periods with water deficiency conditions are identified on the annual ombrothermic graphs when the precipitation data bar drops below the temperature data curve. On the ombrothermic graphs, periods during which plants are under low-temperature stress are indicated when the temperature curve drops below the freezing mark of 0.0° C (32.0° F). The long-term ombrothermic graph for the DREC Ranch (figure 2) shows that near water deficiency conditions exist for August, September, and October. This finding indicates that range plants generally may have a difficult time growing and accumulating herbage biomass during these 3 months. Favorable water relations occur during May, June, and July, a condition indicating that range plants should be able to grow and accumulate herbage biomass during these 3 months.

The ombrothermic relationships for the Dickinson Research Extension Center Ranch in western North Dakota are shown for each month in table 8. The 40-year period (1982 to 2021) had a total of 240 months during the growing season. Of these growing-season months, 73.0 months had water deficiency conditions, which indicates that range plants were under water stress during 30.4% of the growing-season months (tables 8 and 9): this amounts to an average of 2.0 months during every 6.0-month growing season range plants have been limited in growth and herbage biomass accumulation because of water stress. The converse indicates that only 4.0 months of an average year have conditions in which plants can grow without water stress.

Most growing seasons have months with water deficiency conditions. In only 5 of the 40 years (table 8) did water deficiency conditions not occur in any of the six growing-season months. In each growing-season month of 1982, 2013, 2015, 2016, and 2019, the amounts and distribution of the precipitation were adequate to prevent water stress in plants. Nineteen years (47.50%) had water deficiency for 0.5 to 2.0 months during the growing season. Fifteen years (37.50%) had water deficiency conditions for 2.5 to 4.0 months during the growing season. One year (2.50%), 1988, had water deficiency conditions for 5.0 months during the growing season. None of the 40 years had water deficiency conditions for all 6.0 months of the growing season (table 8). The 6-year period (1987-1992) was a long period with low precipitation; during this period, water deficiency conditions existed for an average of 3.1 months during each growing season, which amounts to 51.33% of this period's growing-season months (table 8).

May, June, and July are the 3 most important precipitation months and therefore constitute the primary period of production for range plant communities. May and June are the 2 most important months for dependable precipitation. Only 4 (10.00%) of the 40 years had water deficiency conditions during May, and 6 years (15.00%) had water deficiency conditions during June. One year (2017) had water deficiency conditions in both May and June. Fourteen (35.00%) of the 40 years had water deficiency conditions in July (table 9). Only one year (2017) has had water deficiency conditions during May, June, and July (table 8b).

Most of the growth in range plants occurs in May, June, and July (Goetz 1963, Manske 1994b). Peak aboveground herbage biomass production usually occurs during the last 10 days of July, a period that coincides with the time when plants have attained 100% of their growth in height (Manske 1994b). Range grass growth coincides with the 3-month period of May, June, and July, when 47.30% of the annual precipitation occurs.

August, September, and October are not dependable for positive water relations. August and September had water deficiency conditions in 45.00% and 52.50% of the years, respectively, and October had water deficiency conditions in 35.00% of the years (table 9). Visual observations of range grasses with wilted, senescent leaves in August indicate that most plants experience some level of water stress when conditions approach those of water deficiency. August, September, and/or October had water deficiency conditions during 82.50% of the growing seasons in the previous 40 years (table 8). These 3 months make up 42% of the growing season, and they had water deficiency conditions on the average of 45% of the time (table 9). The water relations in August, September, and October limit range plant growth and herbage biomass accumulation.

Over the last 40 years, drought years occurred 12.5% of the time. Drought growing seasons occurred 12.5% of the time. Water deficiency months occurred 30.4% of the time. Water deficiency occurred in May and June 10.0% and 15.0% of the time, respectively. July had water deficiency conditions 35.0% of the time. August, September, and October had water deficiency conditions more than 45% of the time. Water deficiency periods lasting for a month place plants under water stress severe enough to reduce herbage biomass production. These levels of water stress are a major factor limiting the quantity and quality of plant growth in western North Dakota and can limit livestock production if not considered during the development and implementation of long-term grazing management strategies.

The ombrothermic procedure to identify growing season months with water deficiency treats each month as an independent event. Precipitation during the other months of the year may buffer or enhance the degree of water stress experienced by perennial plants during water deficiency months. The impact of precipitation during other months on the months with water deficiency can be evaluated from annual running total precipitation data (table 10). Water deficiency conditions occurred during 3.5 months in 2021 (table 10).

Conclusion

The vegetation in a region is a result of the total effect of the long-term climatic factors for that region. Ecologically, the most important climatic factors that affect rangeland plant growth are light, temperature, water (precipitation), and water deficiency.

Light is the most important ecological factor because it is necessary for photosynthesis. Changes in time of year and time of day coincide with changes in the angle of incidence of the sun's rays; these changes cause variations in light intensity. Daylight duration oscillation for each region is the same every year and changes with the seasons. Shading of sunlight by cloud cover and from other plants affects plant growth. Day-length period is important to plant growth because it functions as a trigger to physiological processes. Most cool-season plants reach flower phenophase between mid May and mid June. Most warm-season plants flower between mid June and mid September.

Plant growth is limited by both low and high temperatures and occurs within only a narrow range of temperatures, between 32° and 122° F. Perennial plants have a 6-month growing season, between mid April and mid October. Diurnal temperature fluctuations of warm days and cool nights are beneficial for plant growth. Cool-season plants have lower optimum temperatures for photosynthesis than do warm-season plants, and cool-season plants do not use water as efficiently as do warm-season plants. Temperature affects evaporation rates, which has a dynamic effect on the annual ratios of cool-season to warm-season plants in the plant communities. A mixture of cool- and warm-season plants is highly desirable because the grass species in a mixture of cool- and warm-season species have a wide range of different optimum temperatures and the herbage biomass production is more stable over wide variations in seasonal temperatures.

Water is essential for living systems. Average annual precipitation received at the DREC Ranch is 17.0 inches, with 84.7% occurring during the growing season and 47.3% occurring in May, June, and July. Plant water stress occurs when the rate of water loss through transpiration exceeds the rate of replacement by absorption. Years with drought conditions have occurred 12.5% of the time during the past 40 years. Growing seasons with drought conditions have occurred 12.5% of the time.

Water deficiencies exist when the amount of rainfall received is less than evapotranspiration demand. Temperature and precipitation data can be used in ombrothermic graphs to identify monthly periods with water deficiencies. During the past 40 years, 30.4% of the growing-season months had water deficiency conditions that placed range plants under water stress: range plants were limited in growth and herbage biomass accumulation for an average of 2.0 months during every 6-month growing season. May, June, and July had water deficiency conditions 10.0%, 15.0%, and 35.0% of the time, respectively. August, September, and October had water deficiency conditions 45.0%, 52.5% and 35.0% of the time, respectively. One month with water deficiency conditions causes plants to experience water stress severe enough to reduce herbage biomass production.

Most of the growth in range grasses occurs in May, June, and July. In western North Dakota, 100% of range grass leaf growth in height and 86% to 100% of range flower stalk growth in height are completed by 30 July. Peak aboveground herbage biomass production usually occurs during the last 10 days of July, a period that coincides with the time during which plants are attaining 100% of their height. Most range grass growth occurs during the 3-month period of May, June, and July, when 47.3% of the annual precipitation occurs.

Grassland management should be based on phenological growth stages of the major grasses and can be planned by calendar date. Management strategies for a region should consider the climatic factors that affect and limit range plant growth.

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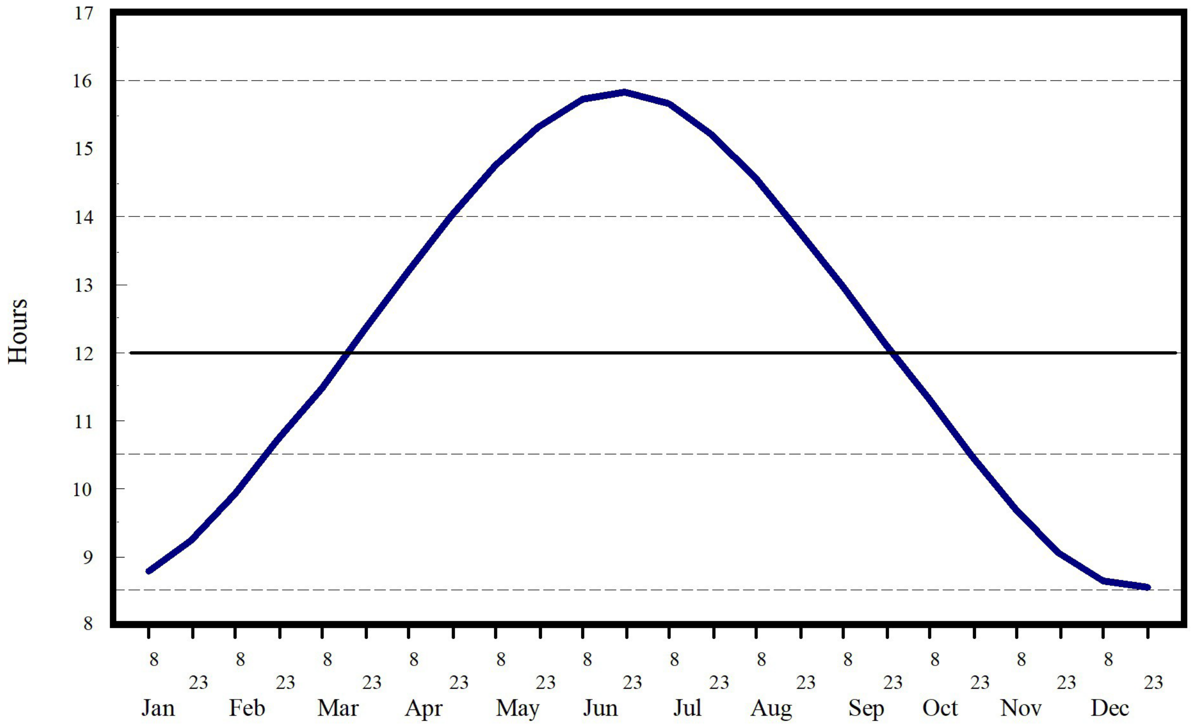

Figure. 1. Annual pattern of daylight duration at Dickinson, North Dakota.

Table 1. Long-term mean monthly temperature and monthly precipitation, 1982-2021.

	°F	°C	in.	mm
Jan	14.97	-9.46	0.43	11.03
Feb	18.11	-7.72	0.44	11.30
Mar	29.45	-1.42	0.74	18.78
Apr	41.44	5.24	1.38	35.00
May	53.52	11.95	2.64	67.13
Jun	63.26	17.37	3.10	78.69
Jul	69.69	20.94	2.31	58.57
Aug	68.39	20.22	2.00	50.75
Sep	56.32	13.96	1.65	41.79
Oct	43.73	6.51	1.33	33.90
Nov	29.33	-1.48	0.54	13.69
Dec	18.21	-7.66	0.46	11.77
	MEAN		**TOTAL**	
	42.20	**5.70**	**17.02**	**432.40**

Table 2. Seasonal precipitation distribution, 1982-2021.

Season	in.	%
Winter (Jan, Feb, Mar)	1.61	9.46
Spring (Apr, May, Jun)	7.12	41.83
Summer (Jul, Aug, Sep)	5.96	35.02
Fall (Oct, Nov, Dec)	2.33	13.69
TOTAL	**17.02**	

Table 3. Precipitation in inches and percent of long-term mean for perennial plant growing season months, 1982-2021.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2021	1.38	2.64	3.10	2.31	2.00	1.65	1.33	14.41	17.02
1982	1.37	2.69	4.30	3.54	1.75	1.69	5.75	21.09	25.31
% of LTM	99.28	101.89	138.71	153.25	87.50	102.42	432.33	146.43	148.68
1983	0.21	1.53	3.26	2.56	4.45	0.86	0.72	13.59	15.55
% of LTM	15.22	57.95	105.16	110.82	222.50	52.12	54.14	94.36	91.34
1984	2.87	0.00	5.30	0.11	1.92	0.53	0.96	11.69	12.88
% of LTM	207.97	0.00	170.97	4.76	96.00	32.12	72.18	81.17	75.66
1985	1.24	3.25	1.58	1.07	1.84	1.69	2.13	12.80	15.13
% of LTM	89.86	123.11	50.97	46.32	92.00	102.42	160.15	88.87	88.88
1986	3.13	3.68	2.58	3.04	0.46	5.29	0.18	18.36	22.96
% of LTM	226.81	139.39	83.23	131.60	23.00	320.61	13.53	127.48	134.88
1987	0.10	1.38	1.15	5.39	2.65	0.78	0.08	11.53	14.13
% of LTM	7.25	52.27	37.10	233.33	132.50	47.27	6.02	80.06	83.00
1988	0.00	1.85	1.70	0.88	0.03	0.73	0.11	5.30	9.03
% of LTM	0.00	70.08	54.84	38.10	1.50	44.24	8.27	36.80	53.04
1989	2.92	1.73	1.63	1.30	1.36	0.70	0.96	10.60	13.07
% of LTM	211.59	65.53	52.58	56.28	68.00	42.42	72.18	73.60	76.78
1990	2.03	2.39	3.75	1.13	0.31	0.68	0.85	11.14	11.97
% of LTM	147.10	90.53	120.97	48.92	15.50	41.21	63.91	77.35	70.31
1991	1.97	1.16	3.95	1.43	0.55	2.17	1.31	12.54	13.30
% of LTM	142.75	43.94	127.42	61.90	27.50	131.52	98.50	87.07	78.13
1992	0.81	0.68	1.59	2.70	2.02	0.72	0.16	8.68	11.23
% of LTM	58.70	25.76	51.29	116.88	101.00	43.64	12.03	60.27	65.97
1993	1.41	1.71	4.57	5.10	1.24	0.18	0.05	14.26	17.36
% of LTM	102.17	64.77	147.42	220.78	62.00	10.91	3.76	99.01	101.98
1994	0.86	1.46	4.51	1.07	0.31	1.08	4.58	13.87	16.14
% of LTM	62.32	55.30	145.48	46.32	15.50	65.45	344.36	96.30	94.81

Table 3 (cont). Precipitation in inches and percent of long-term mean for perennial plant growing season months, 1982-2021.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2021	1.38	2.64	3.10	2.31	2.00	1.65	1.33	14.41	17.02
1995	1.01	4.32	0.68	4.62	3.16	0.00	0.67	14.46	16.24
% of LTM	73.19	163.64	21.94	200.00	158.00	0.00	50.38	100.40	95.40
1996	0.14	3.07	1.86	2.55	1.72	2.51	0.09	11.94	15.97
% of LTM	10.14	116.29	60.00	110.39	86.00	152.12	6.77	82.90	93.81
1997	2.89	0.95	5.02	5.41	0.76	1.75	0.78	17.56	18.61
% of LTM	209.42	35.98	161.94	234.20	38.00	106.06	58.65	121.92	109.32
1998	0.40	1.51	5.98	2.11	4.60	0.71	4.38	19.69	22.42
% of LTM	28.99	57.20	192.90	91.34	230.00	43.03	329.32	136.71	131.70
1999	1.10	4.93	1.59	1.80	2.70	2.40	0.00	14.52	15.56
% of LTM	79.71	186.74	51.29	77.92	135.00	145.45	0.00	100.82	91.40
2000	1.26	1.90	3.77	2.77	2.74	1.09	1.46	14.99	20.23
% of LTM	91.30	71.97	121.61	119.91	137.00	66.06	109.77	104.08	118.84
2001	2.70	0.53	6.36	4.87	0.00	1.94	0.00	16.40	18.03
% of LTM	195.65	20.08	205.16	210.82	0.00	117.58	0.00	113.87	105.91
2002	1.14	2.18	5.40	4.27	4.24	0.74	0.88	18.85	21.88
% of LTM	82.61	82.58	174.19	184.85	212.00	44.85	66.17	130.88	128.53
2003	1.30	4.34	1.42	2.03	0.82	2.37	0.74	13.02	19.12
% of LTM	94.20	164.39	45.81	87.88	41.00	143.64	55.64	90.40	112.31
2004	0.89	1.31	1.65	2.30	0.93	2.57	3.10	12.75	16.51
% of LTM	64.49	49.62	53.23	99.57	46.50	155.76	233.08	88.53	96.98
2005	0.96	6.01	6.05	0.60	1.52	0.50	1.96	17.60	21.51
% of LTM	69.57	227.65	195.16	25.97	76.00	30.30	147.37	122.20	126.35
2006	2.78	2.82	2.13	0.96	2.87	1.42	2.01	14.99	17.70
% of LTM	201.45	106.82	68.71	41.56	143.50	86.06	151.13	104.08	103.97
2007	1.58	4.64	1.80	1.05	0.78	0.76	0.26	10.87	13.94
% of LTM	114.49	175.76	58.06	45.45	39.00	46.06	19.55	75.47	81.89

Table 3 (cont). Precipitation in inches and percent of long-term mean for perennial plant growing season months, 1982-2021.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2021	1.38	2.64	3.10	2.31	2.00	1.65	1.33	14.41	17.02
2008	0.61	2.79	4.02	1.06	1.02	1.04	1.68	12.22	14.88
% of LTM	44.20	105.68	129.68	45.89	51.00	63.03	126.32	84.85	87.41
2009	1.49	2.47	3.84	3.24	0.95	1.15	1.95	15.09	17.89
% of LTM	107.97	93.56	123.87	140.26	47.50	69.70	146.62	104.77	105.09
2010	1.43	3.70	3.50	1.94	1.39	4.09	0.13	16.18	19.03
% of LTM	103.62	140.15	112.90	83.98	69.50	247.88	9.77	112.34	111.79
2011	1.66	6.87	2.15	2.33	2.70	1.76	0.44	17.91	21.28
% of LTM	120.29	260.23	69.35	100.87	135.00	106.67	33.08	124.35	125.00
2012	2.38	1.58	4.31	1.98	0.82	0.21	2.35	13.63	15.46
% of LTM	172.46	59.85	139.03	85.71	41.00	12.73	176.69	94.64	90.82
2013	1.05	7.55	2.23	2.13	2.81	2.44	3.35	21.56	23.22
% of LTM	76.09	285.98	71.94	92.21	140.50	147.88	251.88	149.70	136.40
2014	1.41	3.73	3.38	0.37	8.84	1.03	0.59	19.35	21.11
% of LTM	102.17	141.29	109.03	16.02	442.00	62.42	44.36	134.35	124.00
2015	0.60	1.65	4.68	2.87	1.69	1.35	1.96	14.80	17.01
% of LTM	43.48	62.50	150.97	124.24	84.50	81.82	147.37	102.76	99.92
2016	3.44	2.26	1.96	3.61	1.86	2.66	1.80	17.59	19.70
% of LTM	249.28	85.61	63.23	156.28	93.00	180.95	135.34	122.13	115.72
2017	1.30	0.84	1.27	0.72	2.67	2.28	0.08	9.16	10.55
% of LTM	94.20	31.82	40.97	31.17	133.50	138.18	6.02	63.60	61.97
2018	0.48	1.22	4.23	2.01	0.55	1.84	0.66	10.99	14.39
% of LTM	34.78	46.21	136.45	87.01	27.50	111.52	49.62	76.31	84.53
2019	1.35	2.52	2.60	1.61	4.70	9.10	1.26	23.14	25.88
% of LTM	97.83	95.45	83.87	69.70	235.00	551.52	94.74	160.67	152.02
2020	0.59	1.45	1.10	2.67	2.56	0.86	0.26	9.49	11.01
% of LTM	42.75	54.92	35.48	115.58	128.00	52.12	19.55	65.89	64.68

Table 3 (cont). Precipitation in inches and percent of long-term mean for perennial plant growing season months, 1982-2021.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2021	1.38	2.64	3.10	2.31	2.00	1.65	1.33	14.41	17.02
2021	0.26	5.07	1.07	1.03	1.63	0.14	2.70	11.90	13.75
% of LTM	18.84	192.05	34.52	44.59	81.50	8.48	203.01	82.62	80.77

Table 4. Years with annual precipitation amounts of 75% or less of the long-term mean (LTM).

	Year	**%LTM**
1	1988	53.04
2	2017	61.97
3	2020	64.68
4	1992	65.97
5	1990	70.31

Table 5. Years with annual precipitation amounts of 125% or more of the long-term mean (LTM).

	Year	**%LTM**
1	2019	152.02
2	1982	148.68
3	2013	136.40
4	1986	134.88
5	1998	131.70
6	2002	128.53
7	2005	126.35
8	2011	125.00

Table 6. Years with growing-season precipitation amounts of 75% or less of the long-term mean (LTM).

	Year	%LTM
1	1988	36.80
2	1992	60.27
3	2017	63.60
4	2020	65.89
5	1989	73.60

Table 7. Years with growing-season precipitation amounts of 125% or more of the long-term mean (LTM).

	Year	%LTM
1	2019	160.67
2	2013	149.70
3	1982	146.43
4	1998	136.71
5	2014	134.35
6	2002	130.88
7	1986	127.48

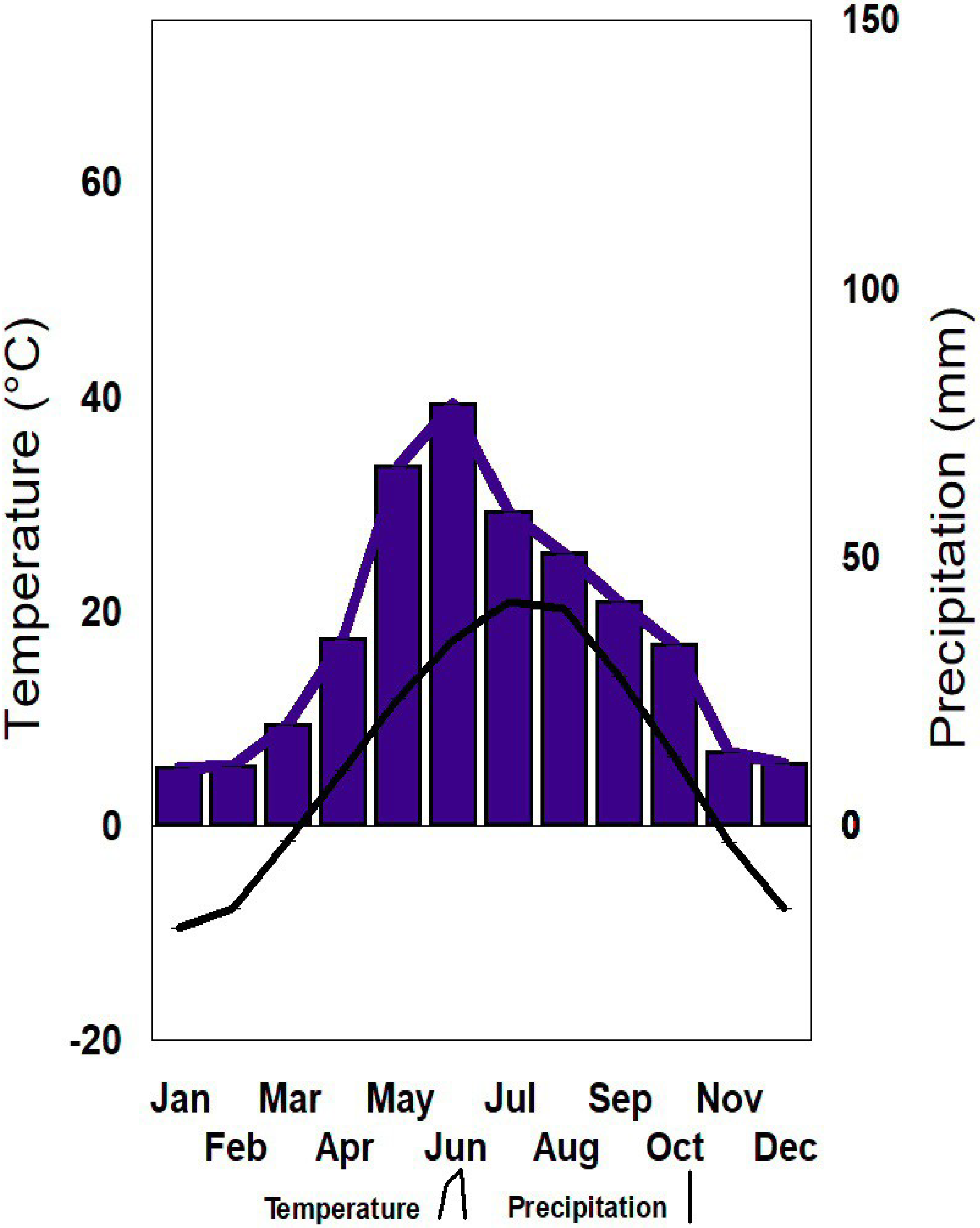

Figure 2. Ombrothermic diagram of long-term mean monthly temperature and monthly precipitation at the DREC Ranch, western North Dakota, 1982-2021.

Table 8a. Growing season months with water deficiency conditions that caused water stress in perennial plants (1982-1989, 1990-1999).

	APR	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**# Months**	**% 6 Months 15 Apr-15 Oct**
1980								-	-
1981	-	-				■		-	-
1982								0.0	0
1983	■					■		1.5	25
1984		■		■		■		3.0	50
1985				■				1.0	17
1986					■		■	1.5	25
1987	■		■			■	■	3.0	50
1988	■		■	■	■	■	■	5.0	83
1989				■	■	■		3.0	50
								18.0	**38**
1990				■	■	■		3.0	50
1991				■	■			2.0	33
1992		■				■	■	2.5	42
1993					■	■	■	2.5	42
1994				■	■	■		3.0	50
1995			■			■		2.0	33
1996	■						■	1.0	17
1997					■			1.0	7
1998	■					■		1.5	25
1999							■	0.5	8
								19.0	**32**

Table 8b. Growing season months with water deficiency conditions that caused water stress in perennial plants (2000-2009, 2010-2019).

	APR	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**# Months**	**% 6 Months 15 Apr-15 Oct**
2000						■		1.0	17
2001		■			■		■	2.5	42
2002						■		1.0	17
2003					■			1.0	17
2004					■			1.0	17
2005				■	■	■		3.0	50
2006				■				1.0	17
2007				■	■	■	■	3.5	58
2008				■	■	■		3.0	50
2009					■	■		2.0	33
								19.0	**32**
2010					■		■	1.5	25
2011							■	0.5	8
2012					■	■		2.0	33
2013								0.0	0
2014				■		■	■	2.5	42
2015								0.0	0
2016								0.0	0
2017		■	■	■			■	3.5	58
2018					■			1.0	17
2019								0.0	0
								11.0	**18**

Table 8c. Growing season months with water deficiency conditions that caused water stress in perennial plants (2020-2029, 2030-2039).

	APR	MAY	JUN	JUL	AUG	SEP	OCT	# Months	% 6 Months 15 Apr-15 Oct
2020			■			■	■	2.5	42
2021	■		■	■		■		3.5	58
2022									
2023									
2024									
2025									
2026									
2027									
2028									
2029									
								6.0	**50**
2030									
2031									
2032									
2033									
2034									
2035									
2036									
2037									
2038									
2039									

Table 9. Growing season months with water deficiency, 1982-2021.

	APR	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**# Months**	**% 6 Months 15 Apr-15 Oct**
TOTAL	6	4	6	14	18	21	14	73.0	30
% of 40 YEARS	15.0	10.0	15.0	35.0	45.0	52.5	35.0		

Table 10. Monthly precipitation and running total precipitation compared to the long-term mean (LTM), 2021.

	Monthly Precipitation (in)			Running Total Precipitation (in)		
Months	LTM 1982-2020	Precipitation 2021	% of LTM	Running LTM 1982-2020	Running Precipitation 2021	% of LTM
Jan	0.44	0.34	77.27	0.44	0.34	77.27
Feb	0.44	0.47	106.82	0.88	0.81	92.05
Mar	0.75	0.25	33.33	1.63	1.06	65.03
Apr	1.41	0.26	18.44	3.04	1.32	43.42
May	2.58	5.07	196.51	5.62	6.39	113.70
Jun	3.15	1.07	33.97	8.77	7.46	85.06
Jul	2.34	1.03	44.02	11.11	8.49	76.42
Aug	2.01	1.63	81.09	13.12	10.12	77.13
Sep	1.68	0.14	8.33	14.80	10.26	69.32
Oct	1.30	2.70	207.69	16.10	12.96	80.50
Nov	0.54	0.40	74.07	16.64	13.36	80.29
Dec	0.47	0.39	82.98	17.11	13.75	80.36
Total	17.11	13.75	80.36		13.75	80.36

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Biologically Effective Management of Northern Plains Grasslands using Ecologically Scientific Principles

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The goals of Biologically Effective Management are to meet the biological requirements of the grass plants and the rhizosphere microbes and the nutrient requirements of the graminivores and to activate the internal grass plant growth mechanisms and the ecosystem biogeochemical processes, in order to revitalize soil structure and functionality, increase forage productivity and nutritional quality, and improve livestock growth and weight performance along with the capture of greater wealth per acre without depletion of future production.

Northern Plains grasslands are complex ecosystems, that are exceedingly more complex than the most complicated machines ever built by humans. Grassland ecosystems are composed of biotic and abiotic components. The indispensable biotic components are grass vegetation, rhizosphere organisms, and grazing graminivores which have biological and physiological requirements that must be met. The abiotic components include radiant energy from sunlight, the climatic factors of precipitation and temperature, with the related conditions of wet and deficient water, and high and low heat, the major essential elements of carbon, hydrogen, nitrogen, and oxygen, the minor essential elements of macro- and micro-nutrients required by living organisms, and the environmental conditions of drought and fire.

The long-standing standard process to understand complex biological systems is to initially investigate the separate component parts and their related processes and mechanisms. The gained knowledge of each part combined with the synergistic effects resulting when the parts work together provide the information needed to develop an understanding of the whole ecosystem. This classical concept of biological systems investigation was developed by the Greek philosopher/scientist Aristotle (384-322 BC) who taught that “the whole is greater than the sum of its parts”.

Dr. Warren C. Whitman (c. 1950) and Dr. Harold Goetz (1963) proposed to use this long-standing standard process at the Dickinson Research Extension Center to gain quantitative knowledge of the component parts and provide the understanding of the whole prairie ecosystem that would be used in the development and establishment of scientific standards for proper ecological management of the grasslands of the Northern Plains. This report is the result of over 75 years of research on grassland ecosystems using the standard investigative process.

Indispensable Biotic Components

Grass vegetation, rhizosphere organisms, and large grazing graminivores are the indispensable biotic components of a functional grassland ecosystem. These indispensable biotic components have developed complex symbiotic relationships. Large grazing graminivores depend on grass plants for nutritious forage. Grass plants depend on rhizosphere organisms to perform the ecosystem biogeochemical processes that mineralize the essential elements from the soil organic matter. The achlorophyllous rhizosphere organisms depend on grass plants for short chain carbon energy, that is exudated through the roots of lead tillers at vegetative growth stages following partial defoliation by grazing graminivores. Grass plants produce double the leaf biomass than is needed for photosynthesis in order to attract the vital partial defoliation by grazing graminivores on which their physiological internal growth mechanisms depend.

Indispensable Grass Vegetation

Grass Tiller Growth and Development

The dominant type of reproduction in perennial grasses is vegetative tiller growth from axillary buds (Belsky 1992, Chapman and Peat 1992, Briske and Richards 1995, Chapman 1996, Manske 1999) not sexual reproduction and the development of seedlings. The frequency of true seedlings is extremely low, and establishment of an independent seedling in functioning grasslands is difficult and occurs only during years with favorable moisture and temperature conditions (Wilson and Briske 1979, Briske and Richards 1995), in areas of reduced competition from vegetative tillers.

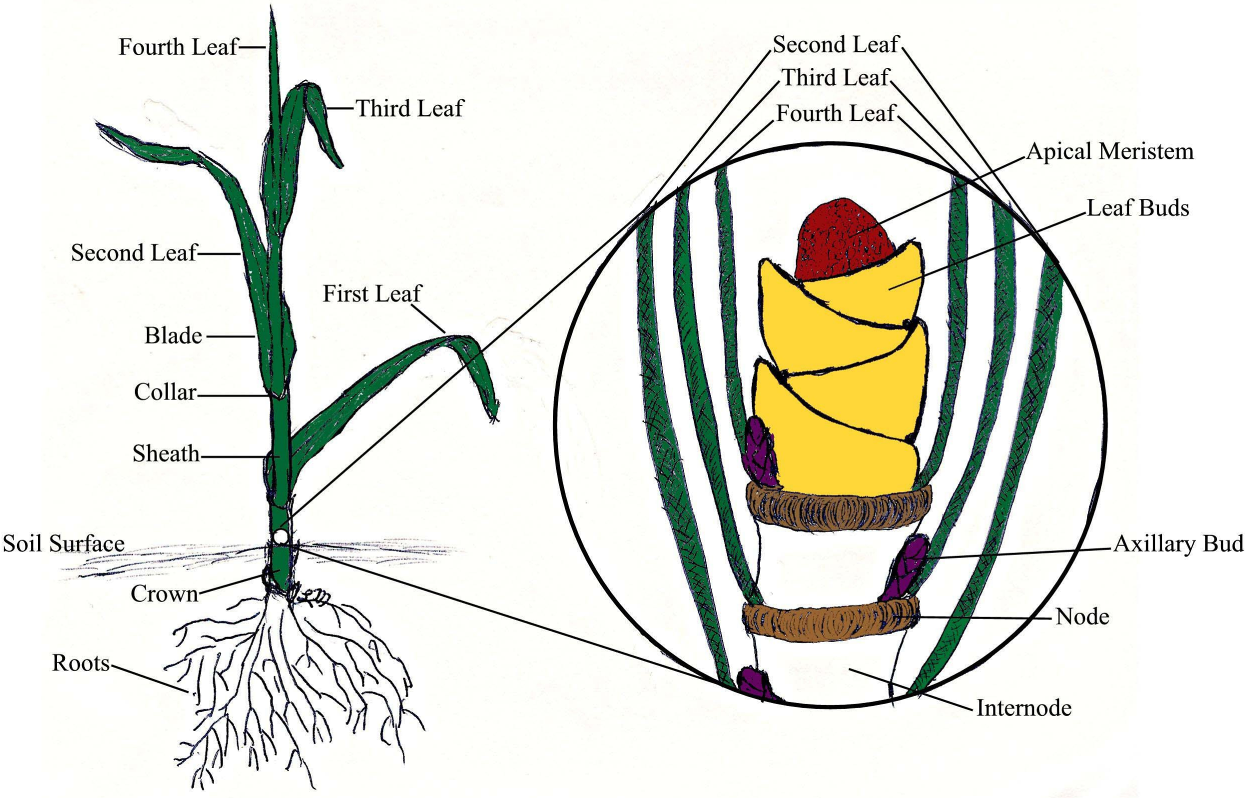
The indispensable grass vegetation provides nutritious forage to large grazing graminivores. Grass plants use the major and minor essential elements in the inorganic form to synthesize vital organic components of carbohydrates, proteins, and nucleotides for structural growth. Grass tillers consist of shoots and roots (figure 1). The shoot is the stem and leaves comprised of repeated phytomers (Beard 1973, Dahl 1995). A phytomer consists of a leaf, with a blade and a sheath separated by a collar, a node, an internode, and an axillary bud (Hyder 1974, Dahl and Hyder 1977). Each tiller shoot produces 6 to 8 phytomers per growing season (Langer 1972, Dahl 1975). The crown of a grass tiller is the lower portion of a shoot and has two or more nodes (Dahl 1995). Fibrous roots grow from crown nodes that are located below ground. The internodes of the crown nodes associated with roots, crown tillers, and rhizome tillers do not elongate (Dahl 1995).

Longevity of grass tillers extends two grazing seasons (Langer 1956, Butler and Briske 1988, Manske 2009, 2014a). Phytomers develop from leaf primordia that form on alternating sides of the apical meristem (Evans and Grover 1940, Langer 1972, Beard 1973, Dahl 1995). Almost all of the phytomer cells are produced in the apical meristem while the leaf primordia is a minute bud (Langer 1972). The oldest cells of a leaf are at the tip, and the youngest cells are at the base (Langer 1972, Dahl 1995). Several leaf primordia are at various stages of development at any one time. The oldest leaf is outermost, while younger leaves grow up through existing leaf sheaths (Rechenthin 1956, Beard 1973). Growth of a leaf results through cell enlargement and elongation (Esau 1960, Dahl 1995). A few new cells are produced by intercalary meristem located at the base of the blade, the base of the sheath, and the base of the internode (Esau 1960). Cell expansion occurs in the region protected by the sheaths of older leaves. When the cells emerge and exposed to light, expansion ceases and photosynthesis and transpiration begin (Langer 1972). Once a leaf blade is fully expanded no further growth of that blade is possible (Dahl 1995).

Individual leaves of grass tillers are relatively short lived. Young middle-aged leaves are in their prime when the rate of apparent photosynthesis is maximum and the leaves begin exporting assimilates to other parts (Langer 1972). At this point, the leaf has its greatest dry weight. Leaf senescence, or aging, begins shortly after middle age. Senescence begins at the tip, the oldest part of the leaf, and spreads downward. As senescence progresses, apparent photosynthesis and movement of assimilates from the leaf to the other parts of the plant decrease (Langer 1972). The rate of senescence occurs at about the same rate as leaf appearance but is influenced by environmental conditions. Dryer soils increase rate of leaf senescence. During senescence, cell constituents are mobilized and redistributed to other parts of the plant (Beard 1973). This process causes weight of the leaf to decrease (Leopold and Kriedemann 1975). The percentage of dryness in a leaf blade is an indication of the degree of senescence.

Grass tillers remain vegetative during the first growing season, over winter, and resume growth as a lead tiller during the second subsequent growing season (Briske and Richards 1995) and generally does not exceed two growing seasons (Langer 1956, Butler and Briske 1988). Production of new leaf primordia continues until the status of the apical meristem changes from vegetative to reproductive (Dahl 1995, Briske and Richards 1995). Initiation of the reproductive growth stages is triggered during the second growing season by photoperiod (Roberts 1939, Dahl 1975) but can be slightly modified by temperature and precipitation (McMillan 1957, Dahl and Hyder 1977). Florally induced lead tillers develop sexual reproductive structures, the apical meristem ceases the production of leaf primordia and begins production of flower primordia when the lead tiller is between the third new leaf stage and the three and a half new leaf stage (Frank 1996, Frank et al. 1997). Previously formed leaf buds continue to grow and develop (Esau 1960, Langer 1972) until the flower stalk elongates (Dahl 1995). The flower bud primordia develop into the inflorescence with the apical dome becoming the terminal spikelet (Langer 1972). The life cycle of a lead grass tiller terminates during the end of the second growing season because production of additional leaves is no longer possible (Briske and Richards 1995).

Figure 1. Grass Tiller Structures.



Grass Tiller at 3.5 Leaf Stage

Grass Plant Mechanisms

The previous concepts, before 2005, on how the evolutionary development of ancestral grasses occurred has been completely changed with the recent discovery of grass microfossils from the Cretaceous as old as 113 Ma (Manske 2022). This doubles the known age of grasses, which was 56 Ma from the Cenozoic. The much longer developmental timeline drastically changes the conditions of grass evolution. The early ancestral grasses developed in the closed canopy of gymnosperm forests that had a relatively warm wet habitat with no water deficiencies nor cold temperatures. The ancestral grasses had greatly reduced flower structures and were wind pollinated. They had a common trait that prevented cellular dehydration, but they could not survive very long in direct sunlight, or low temperatures, and they could not fully repair physical damage to leaves, stems, or roots. By the mid Cretaceous, the rapid angiosperm radiation was replacing the gymnosperms. Dense angiosperm trees grew along rivers, but open habitats of angiosperm shrubs and herbs were greatly increasing. In order for grasses to progress, they had to develop several complex survival mechanisms.

Mechanisms for Adaptation to Dry Open Habitats

With open habitats increasing, the ancestral grasses of the PACMAD clade and the Pooideae subfamily from the BOP clade shifted from the relatively wet environments of closed habitats with no water stress to drier open habitats with variable degrees of water stress. This huge shift in habitat conditions required the development of adaptive mechanisms to dry open habitats. These grasses developed deep branching fibrous roots with symbiotic arbuscular mycorrhizal fungi to absorb water and nutrients from the soil. They had to develop mechanisms to control the rate of water loss in order to prevent cellular dehydration but they had to have enough flexible responsiveness to be able to regulate and control gas exchange. These grasses also developed an elaborate vascular tissue system, complex leaves with water proof cuticles, and complex stomata with dumbbell shaped guard cells and lateral subsidiary cells. The grasses developed bulliform cells to roll or fold the leaves to reduce water loss. These improved structures provided fast action response to environmental changes in water balance resulting in improved water use efficiency permitting grasses to live in open habitats, with water deficient environments and still maintain significant biomass production. These grasses also developed mechanisms and phytohormones to repair and recover from tissue damage caused during water deficient conditions (Wang and Chen 2020).

Grazing Defense Mechanisms

Coincidental with the rapid diversification and great radiation of angiosperms came a huge improvement in the quantity and quality of available forage during the mid Cretaceous which resulted in an extensive explosion of new herbivorous dinosaurs (Manske 2022). Grasses were most likely not a major portion of the dinosaurs diet during the early stages, but a result of curiosity feeding. Within a short period, the intensified grazing pressure on grass ancestors from herbivorous dinosaurs became an important driver that influenced the development of grazing defense mechanisms. The grazing pressure from herbivorous dinosaurs required ancestral grasses to produce a low growing point below grazing height, to produce double the herbage biomass greater than the leaf area needed for photosynthesis, to develop the structures and hormone systems to greatly improve water use efficiency, to develop a complex system for compensatory physiological growth from meristematic tissue that can rapidly assimilate newly fixed carbon and microbial mineral nitrogen to replace grazed leaf and stem structures, to develop a highly competitive belowground system with symbiotic fungi for uptake of soil water and nutrients, to produce meristematic tissue in axillary buds and a controlling hormone feedback system for vegetative reproduction of tillers, and to shed the ability to produce anthiherbivory toxic substances (Manske 2018).

Modern C_3 perennial grasses from the Pooideae subfamily of the BOP clade and grasses with both C_3 and C_4 photosynthesis from several subfamilies of the PACMAD clade possess these same grazing defense mechanisms which means that the development of these mechanisms must have occurred at a very early stage of ancestral grass during the late Early Cretaceous. The development of these grazing defense mechanisms from grazing pressure by herbivorous dinosaurs permit existent grasslands to be the primary forage source for todays livestock production industry.

Cold Tolerance Mechanisms

Ancestral grasses developed in a world of the late Early Cretaceous that was much warmer than the present and grasses did not need cold tolerance mechanisms. The earth started to become cooler during the late Eocene and the Oligocene, 48 to 26

Ma. The dinosaurs had been gone for at least 20 million years. Antarctica had broken away from Gondwana and was moving to the South Pole. Around 33 Ma, the newly opened Southern Ocean permitted the cold circumpolar currents to cause ocean temperatures to drop. Antarctica became frigid and covered with ice, and the global climate became much colder (Retallack 2004).

Grasses that lived in the Temperate Zones had several million years to develop their cold tolerance mechanisms. All grasses shared a common ancestral trait that prevented cellular dehydration, which was also beneficial in the development of cold acclimation responses.

Enhancement of freezing tolerance was provided by a genetically controlled, Poaceae specific, inhibitor of ice recrystallization, by production of a protein (IRIP), which helps prevent cell rupture by ice crystal development (Preston and Sandve 2013, Korner 2016).

Grasses also developed a seasonal phenological cycle with vernalization responsiveness that allows synchronization of vegetative growth and flowering with favorable conditions of spring and activation of autumnal senescence for termination of growth activity before damaging freezing temperatures. Autumnal senescence permits translocation of synthesized compounds from cells downwards to be stored in the crown (Preston and Sandve 2013, Korner 2016). These changes in spring and fall phenological activities are controlled by the local photoperiod (changes in the length of daylight) which is detected by photoreceptors in specialized plant cells.

Perennial grass plants live for, at least, 27 to 43 years (that is the longest time period that data have been collected). With proper management, grass plants could live for an extremely long time. Each grass tiller developed by vegetative growth of axillary buds lives two growing seasons and one winter dormancy season. The maintenance of life in grass plant cells during the winter period depends on stored carbohydrates that are assimilated during the winter hardening process that occurs during mid August to hard frost. The carbohydrates are used for respiration that provides energy for perpetuation of all necessary crown cells, carryover leaves and stems, and the meristematic tissue until they can be reactivated for growth during the following spring. Grass growth outside of the Tropical Zones would not be possible without the development of the cold tolerance mechanisms.

No Drought or Fire Defense Mechanisms

Perennial grass plants living in temperate zones are known to have relatively high survival rates following environmental stressful conditions of drought and fire. However, perennial grasses have no measurable mechanisms activated by either drought or fire events. These usually high survival rates during drought or fire conditions are attributed to the development of mechanisms that have evolved for grass adaptation to living in dry open habitats, to the defense of defoliation by grazing, and to tolerate cold temperatures.

Grass plants have not developed drought defense mechanisms. When grasses transform into summer dormancy because of the lack of soil water, the grasses do not develop to complete dormancy. Grasses appear to maintain the same quantity of active tissue as they do during winter dormancy. As a result of not being able to reach complete summer dormancy, a greater percent of the grass biomass dies during drought conditions than would die if they could develop complete dormancy.

Grass plants have not developed fire defense mechanisms. Fire damages, kills, or consumes the aboveground parts of grasses, and if the soil is dry, some of the belowground parts of grasses. Fire cannot restore degraded grassland ecosystems because fire does not stimulate vegetation reproduction by tillering, fire does not stimulate endomycorrhizal fungal colonization of grass roots, fire does not stimulate rhizosphere organism biomass and activity levels, fire does not stimulate conversion of soil organic nitrogen into inorganic nitrogen, fire does not improve soil water holding capacity, and fire cannot remove woody species that reproduce by vegetative suckers. Repeated fire treatments can modify the composition of the aboveground vegetation in a degraded grassland, but when the fire regime stops, the degraded grassland remains deteriorated. Fire does not improve grassland ecosystems biologically or ecologically, and fire cannot replace the beneficial partial defoliation achieved by grazing graminivores in managing healthy and productive grassland ecosystems.

Internal Grass Growth Mechanisms

The key factor in meeting grass plant biological requirements is proper timing of partial defoliation that removes 25% to 33% of the leaf biomass from grass lead tillers at vegetative growth stages between the 3.5 new leaf stage and the flower (anthesis) stage (1 June to 15 July) that activates the internal grass growth mechanisms that enable grass tillers to withstand and recover from partial defoliation by grazing of large graminivores.

The effects of defoliation are not simply the removal of herbage from grass plants (Langer 1963, 1972): foliage removal disrupts plant growth and photosynthesis, and defoliation also changes physiological mechanisms in all parts of the plant; alters the plant community microclimate by changing light transmission, moisture relations, and temperature (Briske and Richards 1994, 1995); and changes the soil environment, thereby affecting soil organism activity and ecosystem biogeochemical processes (Manske 2000a, 2011a).

Compensatory Physiological Growth

The compensatory physiological growth mechanisms give grass plants the capability to replace lost leaf and shoot biomass following grazing by increasing meristematic tissue activity, increasing photosynthetic capacity, and increasing allocation of carbon and nitrogen (McNaughton 1979, 1983; Briske 1991). Fully activated mechanisms can produce replacement foliage at 140% of the weight that was removed during grazing (Manske 2000b, 2010a, b, 2014a, b). The growth rates of replacement leaves and shoots increase after partial defoliation by grazing. The enhanced activity of meristematic tissue produces larger leaves with greater mass (Langer 1972, Briske and Richards 1995). Developing leaf primordia not fully expanded at time of defoliation have increased growth rates and tend to grow larger than leaves on undefoliated tillers (Langer 1972). Partial defoliated tillers increase photosynthetic rates of remaining mature leaves and rejuvenated portions of older leaves not completely senescent (Atkinson 1986, Briske and Richards 1995). Changes in cytokinin levels and other signals produced as a result of the increase in the root-shoot ratio rejuvenate the photosynthetic apparatus, inhibit or reduce the rate of senescence, and increase the lifespan and leaf mass of remaining mature leaves (Briske and Richards 1995). Activation of the compensatory physiological mechanisms after partial defoliation of grass tillers by grazing requires alternative sources of abundant carbon and nitrogen (Coyne et al. 1995). Carbon fixed during current photosynthesis in remaining mature leaf and shoot tissue and rejuvenated portions of older leaves is preferentially allocated to areas of active meristematic tissue (Ryle and Powell 1975, Richards and Caldwell 1985, Briske and Richards 1995, Coyne et al. 1995). The quantity of leaf area required to fix adequate quantities of carbon is 67% to 75% of the predefoliated leaf area (Manske 1999, 2011a, 2014c). Very little, if any, of the carbon and nitrogen stored in the root system is remobilized to support compensatory growth (Briske and Richards 1995). The mobilizable nitrogen pools in the shoot tissue are reduced following partial defoliation. This loss in nitrogen from the shoot increases preferential use of the quantities of mineral nitrogen available in the media around the roots (Millard et al. 1990, Ourry et al. 1990). This available soil mineral nitrogen has been converted from soil organic nitrogen by active rhizosphere organisms, absorbed through the roots, and moved to areas of active meristematic tissue.

Vegetative Reproduction by Tillering

Vegetative secondary tillers are shoots that develop on lead tillers from growth of axillary buds by the process of tillering (Mueller and Richards 1986, Richards et al. 1988, Murphy and Briske 1992, Briske and Richards 1994, 1995, Dahl 1995) (figure 2). Meristematic activity in axillary buds and the subsequent development of vegetative tillers is regulated by auxin, a growth-inhibiting hormone produced in the apical meristem and young developing leaves (Briske and Richards 1995). Tiller growth from axillary buds is inhibited indirectly by auxin interference with the metabolic function of cytokinin, a growth hormone (Briske and Richards 1995). Partial defoliation of young leaf material at vegetative growth stages temporarily reduces the production of the blockage hormone, auxin (Briske and Richards 1994). This abrupt reduction of plant auxin in the lead tiller allows for cytokinin synthesis or utilization in multiple axillary buds, stimulating the development of vegetative secondary tillers (Murphy and Briske 1992, Briske and Richards 1994). If no defoliation occurs before the flower (anthesis) stage, the lead tiller continues to hormonally inhibit secondary tiller development from axillary buds. Production of the inhibitory hormone, auxin, declines gradationally as the lead tiller reaches the flower stage. The natural reduction of auxin in the lead tiller usually permits only one secondary tiller to develop. This developing secondary tiller produces auxin that hormonally suppress development of additional axillary buds (Briske and Richards 1995). Vegetative tiller growth is the dominant form of reproduction in semiarid and mesic grasslands (Belsky 1992, Chapman and Peat 1992, Briske and Richards 1995, Chapman 1996, Manske 1999) not sexual reproduction and the development of seedlings. Recruitment of new grass plants developed from seedlings is negligible in healthy grassland ecosystems.

Nutrient Resource Uptake

Grass plant dominance within a grassland community is related to the plants competitiveness at nutrient and water resource uptake. Crider (1955) found that grass tillers with 50% or more of the aboveground leaf material removed reduce root growth, root respiration, and root nutrient absorption resulting in reduced functionality of these grass plants. Reduction of active root biomass caused diminishment of grass plant health and vigor (Whitman 1974) that resulted in a loss of resource uptake efficiency and a suppression of the competitiveness of grass plants to take up mineral nitrogen, essential elements, and soil water (Li and Wilson 1998, Kochy 1999, Kochy and Wilson 2000, Peltzer and Kochy 2001). The loss of active root length contributed to the reduction of rhizosphere biomass and the decline of ecosystem biogeochemical processes (Coleman et al. 1983, Klein et al. 1988). The nutrient resource uptake competitiveness of healthy grasses is able to suppress the expansion of shrubs and prevent successful establishment of grass, forb, and shrub seedlings into grasslands (Peltzer and Kochy 2001). The grass growth form has competitive advantages of nutrient uptake over the shrub growth form (Kochy and Wilson 2000). Grass aboveground biomass is primarily productive photosynthetic leaves resulting in a high resource uptake efficiency. Grasses are good competitors for belowground nutrient resources and superior competitors for mineral nitrogen because of a high root: shoot ratio and no woody stems to maintain. Shrubs have a great reduction in resource uptake efficiency because a large portion of the photosynthates produced in the leaves must be used to build and maintain their unproductive woody stems. However, the taller woody stems make shrubs superior competitor for aboveground sunlight resources (Kochy and Wilson 2000). Competition for belowground nutrient resources from healthy grasses reduce the growth rates of shrub rhizomes and cause high mortality rates of young suckers (Li and Wilson 1998). Shrubs can compete for some of the belowground resources only after the grass plants have been degraded by ineffective management. Following the reduction in grass plant resource uptake competitiveness, the belowground resources no longer consumed by the smaller, less vigorous degraded grasses, are taken up by the shrub plants resulting in proportional increases of biomass production (Kochy and Wilson 2000). With greater nutrient resources, shrub rhizome suckers are able to establish a faster growth rate and a higher survival rate (Li and Wilson 1998). The resulting greater shrub stem density increases the competition for the aboveground resources of light causing strong suppression of the grasses (Kochy and Wilson 2000). Traditionally, the observation of increasing woody shrubs and trees into degraded grasslands would have been explained as a result of fire suppression (Humphrey 1962, Stoddart, Smith, and Box 1975, Wright and Bailey 1982).

Water Use Efficiency

Grasslands of the Northern Plains managed with traditional practices are notorious for their inhibitory deficiency in available soil mineral nitrogen (Goetz et al. 1978) which has been determined to cause the observed low herbage production. Deficiencies in mineral nitrogen limit herbage production more often than water in temperate grasslands (Tilman 1990). The total herbage biomass production on grassland ecosystems has been shown to increase with increases in the quantity of available soil mineral nitrogen (Rogler and Lorenz 1957; Whitman 1957, 1963, 1976; Smika et al. 1965; Goetz 1969, 1975; Power and Alessi 1971; Lorenz and Rogler 1972; Taylor 1976; Wight and Black 1979). Greater quantities of available soil mineral nitrogen has been shown to also cause the soil water use efficiency to improve in grassland plants (Smika et al. 1965, Wight and Black 1972, Whitman 1976, 1978). Using a proxy method, Wight and Black (1972) found that precipitation (water) use efficiency of grass plants improved when soil mineral nitrogen was available at threshold quantities of 100 lbs/ac and greater. The inhibitory deficiencies of mineral nitrogen on grasslands that had less than 100 lbs/ac of available soil mineral nitrogen caused the weight of herbage production per inch of precipitation received to be reduced an average of 49.6% below the weight of herbage produced per inch of precipitation on the grassland ecosystems that had greater than 100 lbs/ac of mineral nitrogen and did not have mineral nitrogen deficiencies (Wight and Black 1979). The efficiency of water use in grass plants function at low levels when mineral nitrogen is deficient and function at high levels when mineral nitrogen is available at threshold quantities of 100 lbs/ac or greater. The level of water use efficiency determines the level of herbage biomass productivity on grasslands.

Manske (2010a, b) found that the threshold quantity of 100 lbs/ac of available mineral nitrogen was also critical for functionality of the vegetative reproduction and the compensatory physiological mechanisms. Both these mechanisms function at high potential levels on grasslands that have 100 lbs/ac or greater available soil mineral nitrogen and do not function or function at extremely low levels on grasslands that have mineral nitrogen deficiencies (Manske 2009, 2010a, b, c, 2011b).

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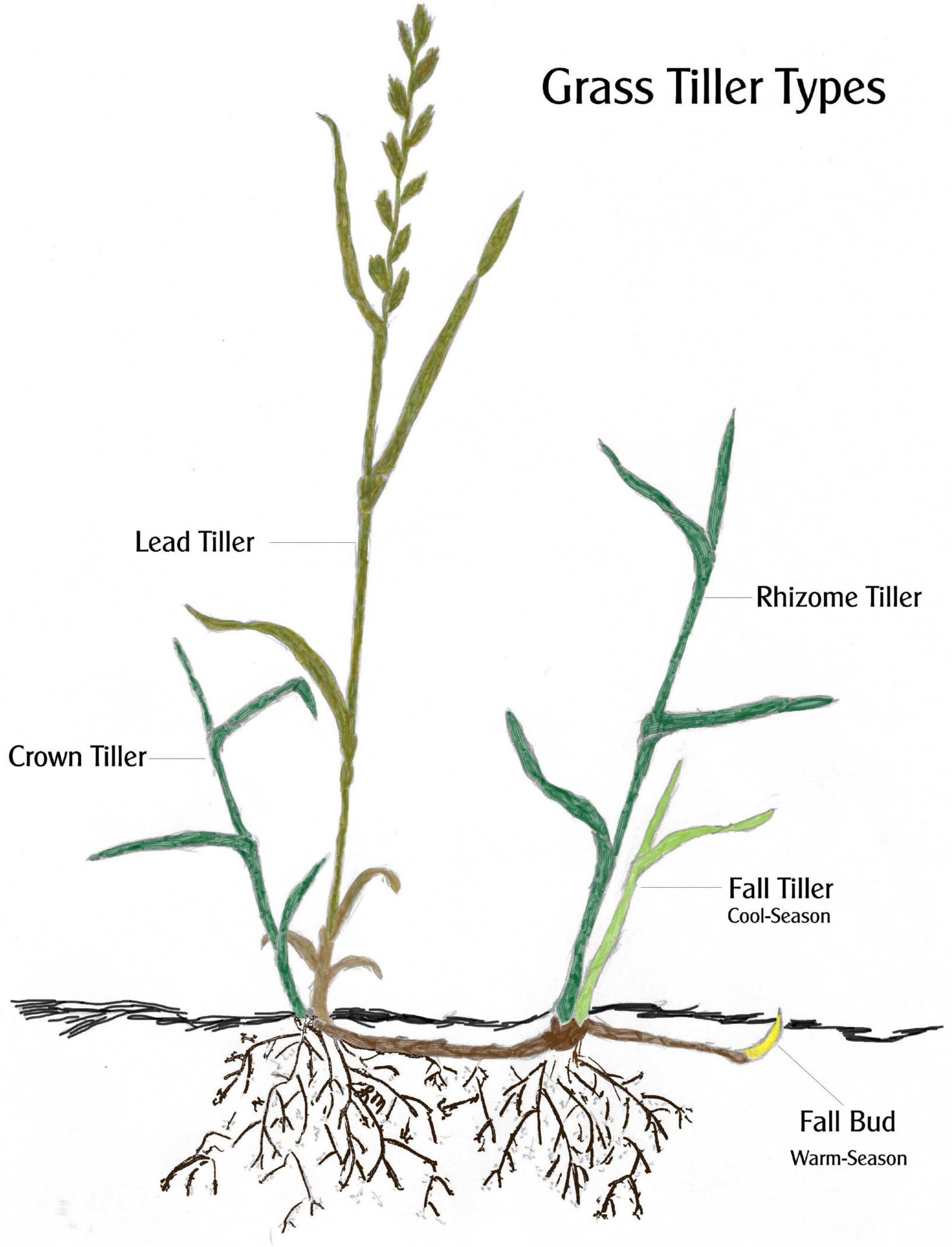

Figure 2. Vegetative Reproduction by Tillering.

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Indispensable Rhizosphere Organisms

Microorganisms of the Rhizosphere

The microbial rhizosphere structure is a cylinder of soil particles bonded by fungal secreted adhesive polysaccharides that surrounds active perennial roots of grassland plants growing in intact soils (figure 1) and the cylinder is inhabited by symbiotic resident organisms and frequent regular visiting organisms. The numerous types of rhizosphere microorganisms are organized along a trophic hierarchy with a means of "communication" among the microbes and with the plant (Manske 2018d). The resident organisms are bacteria, protozoa, and endomycorrhizal fungi and the visiting organisms are nematodes, springtails, and mites (Elliot 1978, Anderson et al. 1981, Harley and Smith 1983, Curl and Truelove 1986, Whipps 1990, Campbell and Greaves 1990) and another resident organism is ectomycorrhizal fungi (Caesar-TonThat et al. 2001b, Manske and Caesar-TonThat 2003, Manske 2007). The numerous types of bacteria have low carbon content. Bacteria are microscopic single celled saprophytic organisms that collectively consume large quantities of soil organic matter and are major primary producers of the rhizosphere (figure 2). Increases in biomass and activity of the bacteria trophic level elevates the concentration of respiratory carbon dioxide (CO_2) resulting in stimulation of activity in the other rhizosphere organisms. Protozoa are single celled microorganisms that are mainly small amoeba in grassland soils and feed primarily on bacteria (figure 3).

The slightly larger rhizosphere organisms are mobile and move among various rhizosphere structures. Nematodes are a diverse group of small nonsegmented worms (figure 4). Most nematodes feed primarily on bacteria or fungi, some feed on protozoa, and some eat other nematodes. Springtails are among the most abundant insect in grassland soils that travel among rhizosphere structures (figure 5). Minute springtails ingest considerable quantities of soil organic matter in order to eat fungi and bacteria. Mites are small eight-legged arachnids that travel among rhizosphere structures and feed on fungi, nematodes, small insects, and other mites. Mites help distribute fungus spores and bacteria through the soil by carrying them on their exoskeleton (figure 6).

Two types of fungi are resident organisms of the rhizosphere; Endomycorrhizal fungi (figure 7) and Ectomycorrhizal fungi (figure 8). Endomycorrhizal fungi are also major primary producers of the rhizosphere and are achlorophyllous saprophytes that live on dead organic matter and cannot fix carbon for energy. Endomycorrhizal fungi develop arbuscules, vesicles, and hyphae within root tissue of the host plant (Harley and Smith 1983) and secrete adhesive polysaccharides that bond soil particles around grass roots forming the structural environment for all rhizosphere organisms. The adhesive polysaccharides also bind soil into aggregates resulting in increased soil pore spaces, increased water holding capacity, and increased rooting depth. Endomycorrhizal fungi also move phosphorus, other macro and micro mineral nutrients, and water through the hyphae to the grass roots for absorption (Moorman and Reeves 1979, Harley and Smith 1983, Allen and Allen 1990, Box and Hammond 1990, Marschner 1992, Koide 1993, Marschner and Dell 1994, Smith and Read 1997).

Ectomycorrhizal fungi develop a sheath around the grass root with hyphae that do not enter the tissue of the host plant (Harley and Smith 1983) and secrete large amounts of adhesive polysaccharides forming water-stable aggregates in soil that are water permeable but not water soluable. The increased soil aggregation improves soil quality, increases soil oxygenation, increases water infiltration, and decreases erodibility (Caesar-TonThat and Cochran 2000, Caesar-TonThat et al. 2001a, Caesar-TonThat et al. 2001b, Caesar-TonThat 2002, Manske and Caesar-TonThat 2003, Manske 2007).

The bacteria and fungi are the microflora saprotrophic organisms at the bottom of the food chain and makeup the greatest biomass of the rhizosphere. Both bacteria and fungi contain high proportions of nitrogen in relation to their carbon content. The microfauna trophic level organisms with normal ratios of carbon to nitrogen, consume bacteria or fungi and ingest greater quantities of nitrogen than they need for a balanced diet based on energy (carbon); the excess nitrogen is excreted as ammonium (NH_4). The endomycorrhizal fungi can nitrify the excreted ammonium into nitrate (NO_3) and pass either form of mineral nitrogen into the grass plant through its endophytic vesicles and arbuscules. The elevated rhizosphere organism activity caused by the increase in available short chain carbon energy exudated from the grass lead tillers following partial defoliation by graminivores results in greater quantities of organic nitrogen mineralized into inorganic nitrogen (Coleman et al. 1983, Klein et al. 1988, Burrows and Pfleger 2002, Rillig et al. 2002, Bird et al. 2002, Driver et al. 2005).

The belowground biogeochemical processes are performed by rhizosphere microorganisms. Grassland soil microflora trophic levels cannot produce their own carbon energy; they lack chlorophyll (achlorophyllous). Also, a large biomass of soil microbes cannot be supported on the small quantities of energy remaining in dead grass roots and leaves. However, grass lead tillers produce large quantities of surplus photosynthate containing short chain carbon energy during vegetative growth stages. This source of carbohydrate energy can be used annually between 1 June and 15 July to feed and sustain a large biomass of rhizosphere microbes (Manske 2018a). The combined weight of the belowground microorganisms on an acre of grassland should be greater than the weight of the largest cow in the herd.

Biogeochemical Processes

The indispensable rhizosphere microorganisms are responsible for the performance of the ecosystem nutrient flow activities and for the ecosystem biogeochemcial processes that determine grassland ecosystem productivity and functionality (Manske 2018d).

Biogeochemical processes transform stored essential elements from organic forms or ionic forms into plant usable mineral forms.

Biogeochemical processes capture replacement quantities of lost or removed major essential elements of carbon, hydrogen, nitrogen, and oxygen with assistance from active live plants and transform the replacement essential elements into storage as soil organic matter for later use.

Biogeochemical processes decompose complex unusable organic material into compounds and then into reusable major and minor essential elements (McNaughton 1979, 1983; Coleman et al. 1983; Ingham et al. 1985; Mueller and Richards 1986; Richards et al. 1988; Briske 1991; Murphy and Briske 1992; Briske and Richards 1994, 1995).

The quantity of biogeochemical processes conducted in grassland ecosystems is dependent on the rhizosphere volume and microorganism biomass (Coleman et al. 1983). Rhizosphere volume and microorganism biomass are limited by access to simple carbohydrate energy (Curl and Truelove 1986). Healthy grass plants produce double the quantity of leaf biomass (Crider 1955, Coyne et al. 1995), capture and fix large amounts of carbon during photosynthesis, and produce carbohydrates in quantities greater than the amount needed for normal growth and maintenance (Coyne et al. 1995). Partial defoliation of grass lead tillers at vegetative phenological growth stages by large grazing graminivores causes greater quantities of exudates containing simple carbohydrates to be released from the grass tillers through the roots into the rhizosphere (Hamilton and Frank 2001). With the increase in availability of carbon compounds in the rhizosphere, the biomass and activity of the microorganisms increases (Anderson et al. 1981, Curl and Truelove 1986, Whipps 1990). The increase in rhizosphere organism biomass and activity results in greater quantities of biogeochemical cycling of essential elements (Coleman et al. 1983, Biondini et al. 1988, Klein et al. 1988, Burrows and Pfleger 2002, Rillig et al. 2002, Bird et al. 2002, Driver et al. 2005).

RHIZOSPHERE STRUCTURE

Figure 1. Rhizosphere with soil particles bound to plant roots by polysaccharides secreted b y mycorrhizal fungi.

MICROFLORA

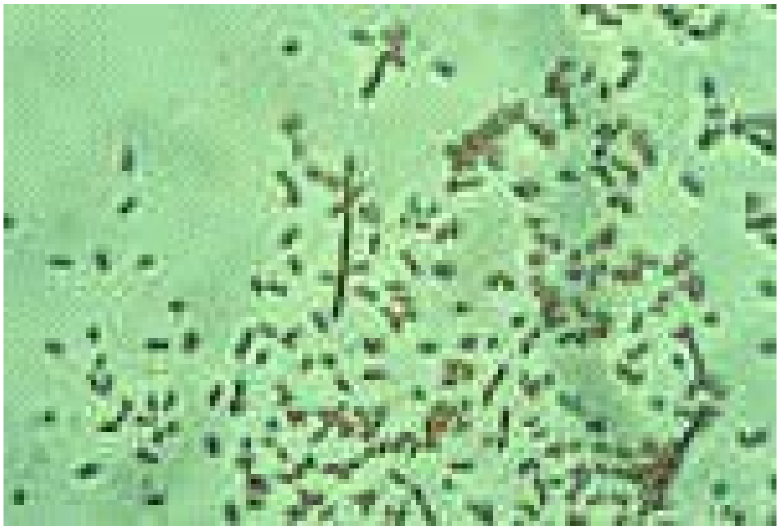

Photo from M.T. Holmes

Figure 2. Bacteria are microscopic single-celled organisms with biomass greater than 2000 pounds per acre.

MICROFAUNA

PROTOZOA

Photo from J.P. Martin

Figure 3. Amoeba ingesting bacteria.
Protozoa are single-celled microorganisms.

NEMATODES

Photo from H. Garrett

Figure 4. Beneficial nematodes are small nonsegmented worms.

SPRINGTAILS

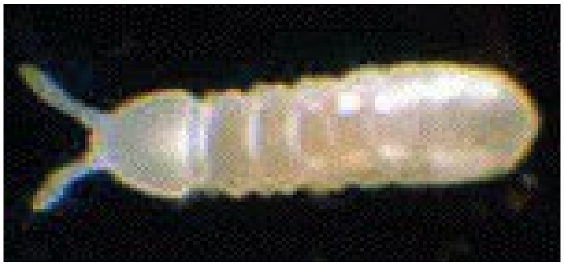

Photo from A.R. Moldenke

Blind fungal-feeding springtail.

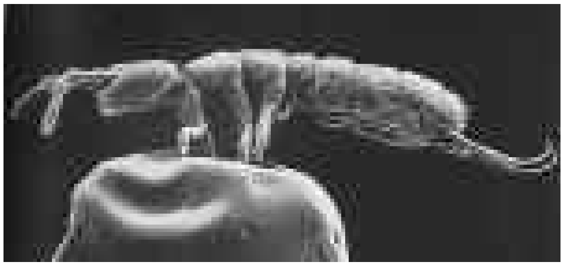

Photo from G. Eisenbeis and W. Wichard

Springtail with furcula released.

Figure 5. Springtails are minute insects.

MITES

Photo from G. Eisenbeis and W. Wichard

Predatory mite.
Figure 6. Mites are small eight-legged arachnids.

MYCORRHIZAL FUNGI

Figure 7. ENDOMYCORRHIZAL FUNGI

Photo from R. Campbell

Fungal hyphae strands with
bacteria on the surface.

Photo from M. Brundrett

Arbuscules and vesicles of a
mycorrhizal fungus within root tissue.

Figure 8. ECTOMYCORRHIZAL FUNGI

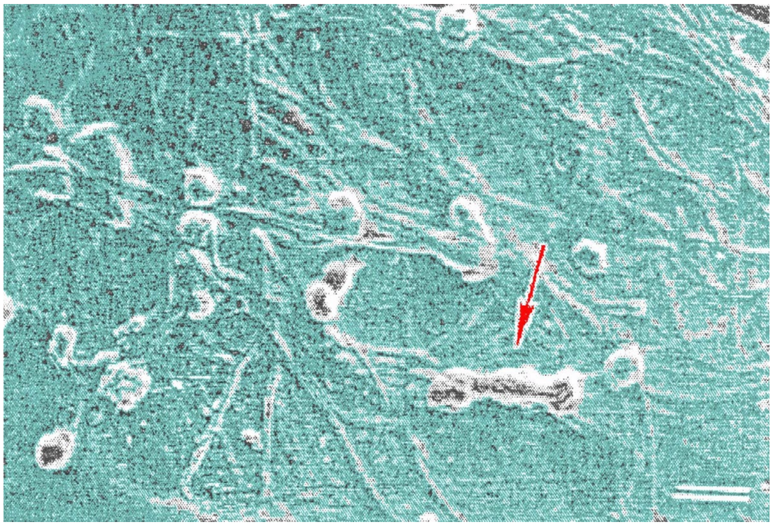

Photo from T.C. Caesar-TonThat

Ectomycorrhizal fungus with extracellular polysaccharides.

Rhizosphere Biomass

Grasslands of the Northern Plains managed with traditional practices are notorious for their inhibitory deficiencies in available soil mineral nitrogen (Goetz et al. 1978) which has been determined to be the major cause for the observed below potential levels of grass herbage production and calf weight gains. Deficiencies in mineral nitrogen limit herbage production more often than water deficiencies in temperate grasslands (Tilman 1990).

Manske (2012) documented quantities of available mineral nitrogen that ranged from 31.2 lbs/ac to 76.7 lbs/ac (34.9-85.9 kg/ha) with a mean of 50.3 lbs/ac (56.3 kg/ha) on five traditional management treatments with operational histories of 20 to 75 years.

Wight and Black (1992) found that grasslands that had less than 100 lbs/ac (112 kg/ha) of available soil mineral nitrogen caused the weight of grass herbage production to be reduced 49.6% below the weight of herbage production on grasslands that had greater than 100 lbs/ac of mineral nitrogen and that did not have mineral nitrogen deficiencies (Wight and Black 1979).

Northern Plains grasslands have been accumulating nitrogen at a few pounds per acre per year for about 5000 years since the current climate started (Bluemle 2000). Lighting discharges combined dinitrogen (N_2) and oxygen (O_2) in the atmosphere to produce nitric acid (NO) and dinitrogen oxide (N_2O) that are deposited on the land in precipitation at a rate around 5 to 6 lbs/ac per year in temperate regions (Brady 1974, Gibson 2009). This nitrogen is stored in the soil as organic nitrogen and not available to plants. Most intact grassland soils have accumulated 5 to 6 tons of organic nitrogen per acre. This organic nitrogen must be transformed into inorganic (mineral) nitrogen by active rhizosphere organisms. Grasslands managed by traditional practices have a mineral nitrogen deficiency problem, but they are not deficient of nitrogen; they are deficient of a large enough biomass of rhizosphere organisms that can transform 100 lbs/ac or greater of mineral nitrogen.

Rhizosphere organism biomass and activity are limited by access to simple carbon chain energy (Curl and Truelove 1986) because the soil microflora trophic levels lack chlorophyll. Grass lead tillers at vegetative growth stages between the 3.5 new leaf stage and the flower (anthesis) stage contain surplus carbohydrates that can be exudated through the plant roots into the rhizosphere (Hamilton and Frank 2001) by partial defoliation of the vegetative lead tillers by grazing graminovores that removes 25% to 33% of the aboveground leaf and shoot weight (Manske 1999). With the increase in availability of energy from simple carbon compounds in the rhizosphere, microorganism activity (Elliot 1978, Anderson et al. 1981, Whipps 1990) and biomass (Gorder, Manske, and Stroh 2004) greatly increase.

To determine the rate of increase of the rhizosphere biomass, a 6 year study was started on a native grassland that had 13 years of nongrazing and was degraded. A twice-over rotation grazing system was initiated compared with a nongrazed control. The pretreatment rhizosphere weight averaged 65 kg/m^3 which would transform less than 30 lbs/ac (33.8 kg/ha) of mineral nitrogen. The response of the rhizosphere microbes to the grazing practice was not instantaneous. The rhizosphere microbes on the nongrazed control treatment had access to only small quantities of plant material leakage from depauperated grass roots. The annual changes in rhizosphere microbe weight on the nongrazed control treatment were small and averaged 6.9 kg/m^3/yr during years 1 to 5. A relatively large change of 50% in microbe weight occurred during year 6 that corresponded with a 28% increase in growing season precipitation (figure 9).

The rhizosphere microbes on the twice-over rotation grazing treatment had access to large quantities of carbon energy. However, even with the increase of carbon energy from the grass lead tillers, the rhizosphere microbe weights were not significantly different from those on the nongrazed control during the first two years. Finally, during year 3, the rhizosphere microbe weights increased 33% and continued to increase at a mean rate of 30.5 kg/m^3 per year from year 3 to 6, reaching a weight of 214.3 kg/m^3, which was 64.2% greater than the microbe weight on the nongrazed control (figure 9). After 6 years of management with the twice-over rotation strategy, the rhizosphere microbes had reached a biomass of 214 kg/m^3 and were mineralizing 99.4 lbs/ac (111.3 kg/ha) of mineral nitrogen (NH_4 and NO_3) (Manske 2018a).

A Standard Reference Rhizosphere Weight of 406.44 kg/m^3 was recorded on silty ecological sites managed by the twice-over rotation grazing strategy after 24 years (Manske 2018d).

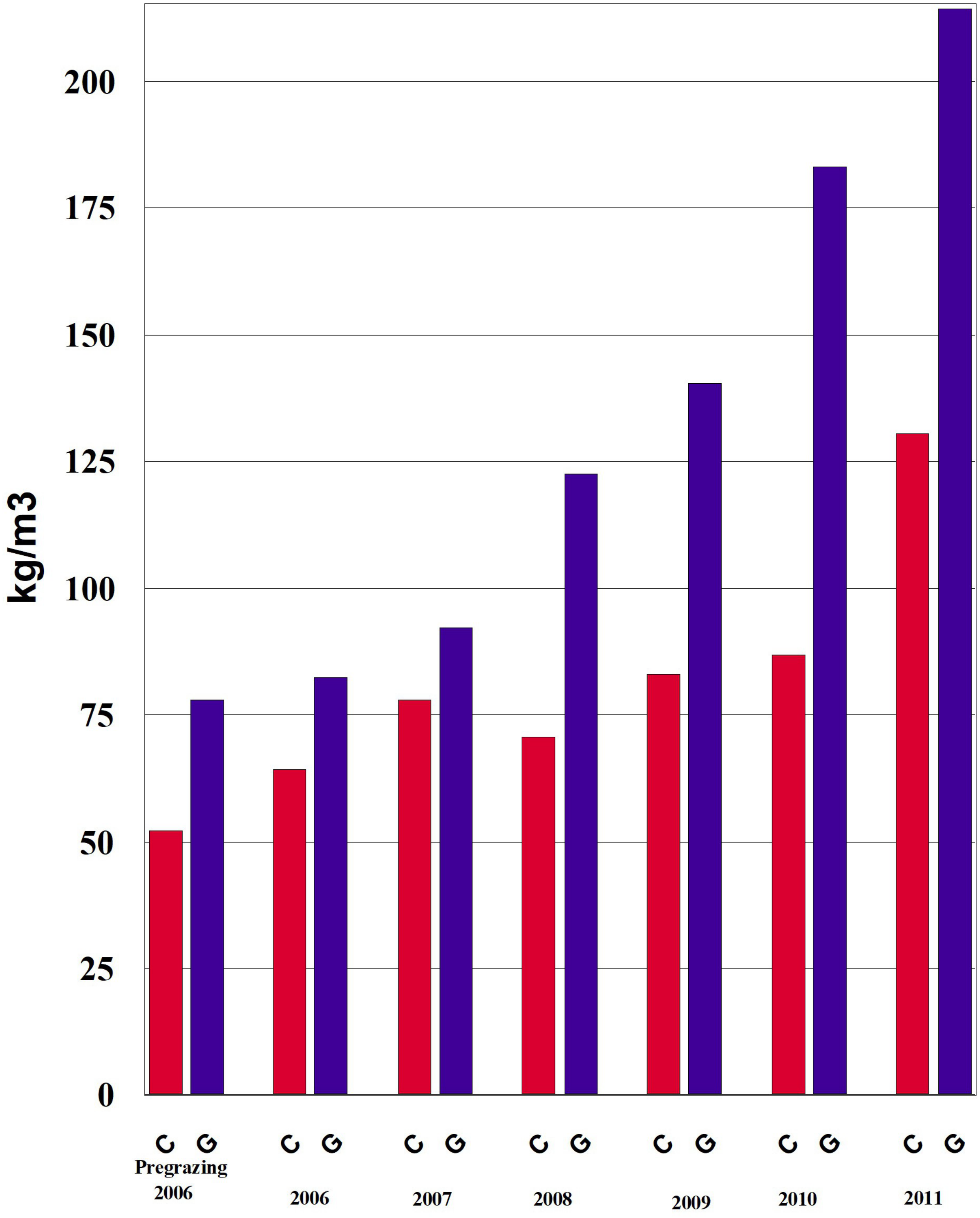

Figure 9. Rhizosphere weight (kg/m3) for the control pasture (red) and grazed pastures (blue) during six years of twice-over rotation management, 2006-2011.

Finding Ectomycorrhizal Fungi

Livestock producers have typically observed changes in the soil structure and quality in their native rangeland pastures after three to five years of management with the twice-over rotation strategy. They notice that shovels are easily pushed into the soil, grass density thickens, grass rooting depth increases 12 to 24 inches deeper, and watershed harvest dams fail to fill because of a decrease in water runoff. These commonly observed changes in native rangeland soils had to have a cause.

These observations continued for many growing seasons with no definitive answer available. Until a McKenzie county, ND, rancher observed a huge difference in his predominately clayey soils that had changed from a rooting depth and water holding soil profile of 2 to 3 inches to an aggregated soil of 18 to 24 inches in depth after seven years of management with a twice-over rotation system. Hence, soil samples from his ranch were collected and taken for analysis by Soil Microbiologist TheCan Caesar-TonThat PhD at her laboratory at USDA Agricultural Research Service, Sidney, MT. She detected the presence of ectomycorrhizal fungi. During the field seasons of 1999 and 2000 replicated soil cores were collected from the sandy and silty ecological sites of pastures managed with the seasonlong and twice-over rotation grazing strategies of the 1983-2018 Study at the Dickinson Research Extension Center ranch located in Dunn County in western North Dakota. The soil samples were analyzed by Dr. Caesar-TonThat in Sidney, MT. The absorbance readings determined the presence of ectomycorrhizal fungi from the Basidiomycota phylum (previous taxon:Homobasidiomycetes class and Russuloid clade order) current taxon: Agaricomycetes class and Russulales order in both the sandy and silty soil cores from the twice-over rotation system but not in the soil cores from the seasonlong system (Manske 2007).

The effects from the twice-over rotation strategy had enhanced the development of ectomycorrhizal fungi in the rhizosphere of mixed grass prairie grasses. Active ectomycorrhizal fungi form water-stable aggregates in soil that are water permeable but not water soluble by secreting large amounts of insoluble extracellular polysaccharides that have adhesive qualities (Caesar-TonThat et al. 2001b). Adhesive polysaccharides act as binding agents for soil particles, causing aggregation of soil (Caesar-TonThat 2002) that range from about the size of air rifle pellets to the size of large marbles. Increases in soil aggregation enlarges soil pore size and improves distribution and stabilization of soil particles. These improvements in soil quality cause increases in soil oxygenation, increases in water infiltration, and decreases in erodibility (Caesar-TonThat and Cochran 2000, Caesar-TonThat et al. 2001a, Caesar-TonThat et al. 2001b, Caesar-TonThat 2002, Manske and Caesar-TonThat 2003). Increased soil aggregation contributes to improvement of grassland ecosystem soil structure and quality increasing productivity.

Acknowledgment

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ECTOMYCORRHIZAL FUNGI

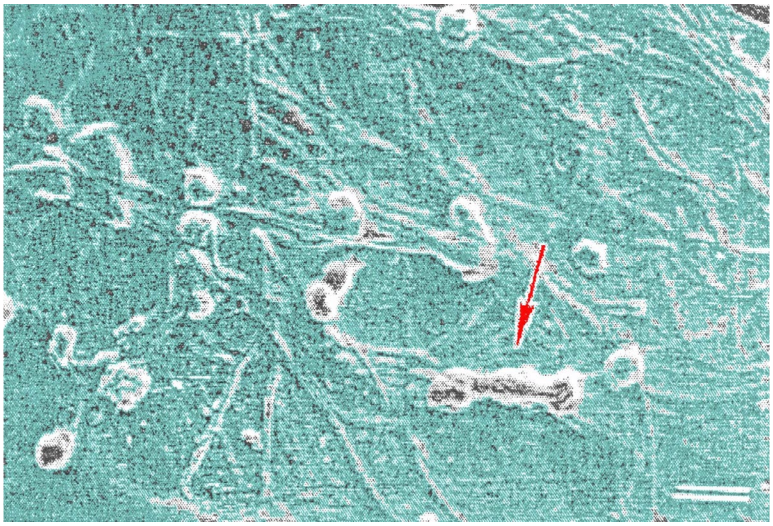

Photo from T.C. Caesar-TonThat
Ectomycorrhizal fungus with extracellular polysaccharides

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Indispensable Grazing Graminivores

Grazing graminivores receive nutritious forage from healthy grass plants. Providing forage for graminivores is not the only purpose for grazing grasslands. Grazing graminivores is biologically beneficial for grass plants and indispensable for grassland ecosystems when grazing periods are coordinated with grass phenological growth stages. The essential rhizosphere microorganisms are achlorophyllous and cannot capture and fix their own energy, and the small quantity of short chain carbon energy naturally leaked from grass plants is too low to support any greater than a tiny biomass of soil microbes. However, partial defoliation by large graminivores of grass lead tillers at vegetative growth stages cause the exudation of large quantities of short chain carbon energy from grass lead tillers through the roots to the rhizosphere microbes. The resulting greater biomass and activity of the soil microbes can transform greater quantities of unusable essential elements from the organic form or ionic form into a plant usable form. A large biomass of rhizosphere microorganisms is required to mineralize a large quantity of unusable organic nitrogen into a threshold yield of 100 lbs/ac of available mineral nitrogen in the forms of ammonium (NH_4) and nitrate (NO_3). The activity of the large biomass of rhizosphere microbes are able to perform all of the ecosystem biogeochemical processes.

Grass growth can occur without partial defoliation by grazing graminivores, however, total herbage biomass production is greatly suppressed without the activation of the grass growth mechanisms of compensatory physiological mechanisms, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency. These four primary physiological grass growth mechanisms that perform the herbage replacement processes are activated with partial defoliation by large grazing graminivores when 25% to 33% of leaf weight is removed from 60% to 80% of lead tillers during vegetative phenological growth stages between the three and a half new leaf stage and the flower stage. When a threshold quantity of 100 lbs/ac of mineral nitrogen is available in the soil and all four grass growth mechanisms are fully activated, grass tillers can produce 140% of the quantity removed from the foliage by grazing which would not have been produced without partial defoliation by grazing graminivores. The replacement herbage produced by the activated grass growth mechanisms will provide adequate quantities of crude protein for the cows between mid July and late September 100% of the years and to mid October 64% of the years (Manske 2018f).

Grazing graminivores remove the 50% surplus grass biomass produced by grass plants before that extra herbage can become detrimental to the ecosystem each growing season. There are no replacement management practices that can perform the indispensable functions that grazing graminivores provide to fully functional grassland ecosystems (Manske 2018e).

Modern Range Cow

Livestock producers have transformed the North American beef herd into high performance, fast-growing meat animals with larger size, increased weight production, improved genetic potential, and greatly increased nutritional demands. The high performance modern cow's requirements for crude protein during lactation have increased 41% to 72%, depending on the quantity of milk produced, greater than that required by the old style range cow (Manske 2018f). The improved animal genetics was intended to solve the problems of high cost, low returns in the beef industry. However, the old traditional concepts of pasture management have not been able to provide the increased levels of nutrients required by modern cows resulting in additional costs or reduced production. Unfortunately, the forage management technology was not improved simultaneously with increased beef cow performance. The forage management paradigms have now been improved. Biologically effective forage management considers both the above - and belowground components of a functional ecosystem and meet the biological requirements of the grass vegetation and the rhizosphere microbes, and the nutrient requirements of the modern livestock (Manske 2018f).

Graminivore's Role on Grasslands

Grazing large graminivores on a fully functional grassland ecosystem can be perpetually sustainable with biologically effective management that activates the ecosystem biogeochemical processes and the grass plant physiological growth mechanisms to function at potential levels. When these processes and mechanisms function above threshold levels, capture and replenishment of input essential elements occurs at greater quantities than the amount of output essential elements. Soil organisms and grass plants use the essential elements in the inorganic form to synthesize vital organic compounds of carbohydrates, proteins, and nucleotides. Grass plants produce double the quantity of leaf biomass than needed for normal plant growth and maintenance (Crider 1955, Coyne et al. 1995). All of the aboveground herbage biomass produced by perennial grasses in a growing season represents about 33% of the total biomass produced. About 67% of the annual perennial grass biomass is produced belowground. About 50% of the aboveground biomass is expendable by the grass plant (Crider 1955). About half of the expendable leaf material is removed as senescent leaves that are broken from the plant and fall to the ground as litter, or removed as leaf material by wildlife, grasshoppers, and other small animals. About half of the expendable leaf material, or 25% of the aboveground grass biomass can be consumed by grazing graminivores (Manske 2012a).

Graminivores grazing grass plants acquire energy, protein, macrominerals, and microminerals from the forage they consume. Perennial grass leaf material consists of both digestible nutrients and nondigestible plant structural components. Adequate quantities of crude protein and energy are available to the graminivores during early June through mid October from the growing forage grass plants on fully functional ecosystems. About 15% of the nutrients contained in the consumed grass leaf material is extracted by stocker heifers and steers and retained for growth. About 30% of the nutrients contained in the consumed grass leaf material is extracted by lactating cows, with a portion retained by the cow for production, and the remainder of the extracted nutrients passed on the her calf for growth (Russelle 1992, Gibson 2009).

All of the nondigestible dry matter and most of the nutrients consumed by grazing graminivores are deposited on the ground as manure in a couple of days. Most of the consumed nutrients extracted and used by graminivores for maintenance are returned to the ecosystem in the feces and urine. None of the herbage biomass dry matter produced during a growing season is removed by graminivores from the grassland ecosystem. All of the essential elements contained in the belowground biomass and contained in the nonconsumed aboveground biomass stay in the ecosystem. Nearly all of the essential elements used in the annual production of grass herbage biomass and soil organism biomass are retained and recycled in the ecosystem.

Some essential elements are lost or removed from the ecosystem as annual output. The metabolic process of respiration of soil organisms, grass plants, graminivores, and other fauna results in a loss of some essential elements as carbon dioxide, water vapor, and heat energy. Some essential elements are removed from the ecosystem as weight biomass produced by insects and wildlife. The essential elements transferred from grass plants to grazing graminivores and used for growth are removed from the ecosystem (Gibson 2009). If the grassland ecosystem is burned, almost all of the essential elements in the aboveground herbage are volatized, and if the soil is dry, some of the belowground essential elements are also lost (Russelle 1992).

Grassland ecosystems degrade when the losses of essential elements is greater than the capture of replacement essential elements. Conversely, grassland ecosystems aggrade when the capture of essential elements is greater than the losses (McGill and Cole 1981). A large biomass of soil microbes and healthy grass plants is required to aggrade grassland ecosystems (Coleman et al. 1983, Schimel, Coleman, and Horton 1985, Cheng and Johnson 1998). When the ecosystem biogeochemical processes and the grass plant physiological mechanisms are functioning at potential levels, a grazed grassland ecosystem is perpetually sustainable (Manske 2013).

Nutritional Requirements

Grazing graminivores depend on grass plants for nutritious forage. The nutrients required by range cows are energy, protein, minerals, vitamins, and water. The quantities of each nutrient required vary with cow weight, level of milk production, and production period. Beef cow production periods are separated into: dry gestation, third trimester, early lactation, and lactation, which is subdivided into spring, summer, and fall portions. The 1200 lb cow is the largest size that can be sustained at biological production levels on the available forage nutrients from native grasslands in the Northern Plains. During lactation, a 1200 lb cow requires 15.23 lbs of energy (TDN) and 2.51 lbs of crude protein per day (table 1) (Manske 2002). The quantity of forage dry matter required to carry that level of energy and protein is different when the cow is not on pasture from the quantity of forage dry matter allocation while the cow is on pasture (table 2). Range cows require large amounts of macrominerals: potassium (K), calcium (Ca), phosphorus (P), magnesium (Mg), sulfur (S), sodium (Na), and chlorine (Cl) (table 3) and require very small amounts of microminerals or trace elements: iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), iodine (I), cobalt (Co), selenium (Se), molybdenum (Mo), chromium (Cr), and nickel (Ni) (table 3) (Manske 2001). Range cows require very large amounts of the major essential elements: carbon (C), hydrogen (H), nitrogen (N), and oxygen (O).

These major and minor essential elements are imperative for life to exist by ensuring growth and development of organisms and the maintenance of all life functions. During a 12-month production cycle a 1200 lb range cow with calf birth in March requires 5217.23 lbs energy (TDN) and 835.80 lbs crude protein carried by 9,489 lbs dry matter with about 35% from harvested forages and 65% from pasture forages (table 4) (Manske 2002).

Table 1. Intake nutrient requirements (lb/d) for modern range cows with average milk production during cow production periods.

Nutrient (lb/d)	Dry Gestation	Third Trimester	Early Lactation	Spring Lactation	Summer Lactation	Fall Lactation
1000 lb cows						
Dry matter	21	21	24	24	24	24
Energy (TDN)	9.64	10.98	14.30	13.73	13.73	13.73
Crude Protein	1.30	1.64	2.52	2.30	2.30	2.30
Calcium	0.03	0.05	0.07	0.06	0.06	0.06
Phosphorus	0.02	0.03	0.05	0.04	0.04	0.04
1200 lb cows						
Dry matter	24	24	27	27	27	27
Energy (TDN)	11.02	12.62	15.85	15.23	15.23	15.23
Crude Protein	1.49	1.87	2.73	2.51	2.51	2.51
Calcium	0.04	0.06	0.08	0.07	0.07	0.07
Phosphorus	0.03	0.04	0.05	0.05	0.05	0.05
1400 lb cows						
Dry matter	27	27	30	30	30	30
Energy (TDN)	12.42	14.28	17.40	16.71	16.71	16.71
Crude Protein	1.67	2.13	2.94	2.70	2.70	2.70
Calcium	0.04	0.07	0.08	0.08	0.08	0.08
Phosphorus	0.03	0.05	0.06	0.05	0.05	0.05

Data from NRC 1996.

Table 2. Daily dry matter allocation (lb/d) for modern range cows grazing pasture forage.

DM lb/d	1000 lb cow	1200 lb cow	1400 lb cow
Dry matter allocation	26	30	33

Date from Manske 2012b.

Table 3. Daily minor essential element requirements of macrominerals (lbs/day) and microminerals (g/day) during six production periods for 1200 lb beef cows with average milk production.

Minor Essential Elements	Dry Gestation	Third Trimester	Early Lactation	Spring Lactation	Summer Lactation	Fall Lactation
Macrominerals (lbs/day)						
Calcium	0.04	0.06	0.08	0.07	0.07	0.07
Phosphorous	0.03	0.04	0.05	0.05	0.05	0.05
Potassium	0.14	0.14	0.19	0.19	0.19	0.19
Magnesium	0.03	0.03	0.05	0.045	0.045	0.045
Sulfur	0.04	0.04	0.04	0.04	0.04	0.04
Sodium	0.01	0.02	0.03	0.03	0.03	0.03
Chlorine	-	-	-	-	-	-
Microminerals (g/day)						
Iron	0.5443	0.5443	0.6124	0.6124	0.6124	0.6124
Manganese	0.4355	0.4355	0.4899	0.4899	0.4899	0.4899
Zinc	0.3266	0.3266	0.3674	0.3674	0.3674	0.3674
Copper	0.1089	0.1089	0.1225	0.1225	0.1225	0.1225
Iodine	0.0054	0.0054	0.0061	0.0061	0.0061	0.0061
Cobalt	0.0011	0.0011	0.0012	0.0012	0.0012	0.0012
Selenium	0.0011	0.0011	0.0012	0.0012	0.0012	0.0012
Molybdenum	-	-	-	-	-	-
Chromium	-	-	-	-	-	-
Nickel	-	-	-	-	-	-

Data from NRC 1996.

Table 4. Twelve-month nutrient requirements for 1200-pound range cows with calf birth dates in March.

	Dry Gestation		3rd Trimester		Early Lactation		Lactation			
	Ration	Pasture	Ration	Pasture	Ration	Pasture	Ration	Spring Pasture	Summer Pasture	Fall Pasture
Days		32	90		45			31	137	30
Daily Requirements in Pounds										
Dry Matter		24	24		27				27	
Energy (TDN)		11.02	12.62		15.85				15.23	
Crude Protein		1.49	1.87		2.73				2.51	
Calcium		0.04	0.06		0.08				0.07	
Phosphorus		0.03	0.04		0.05				0.05	
Production Period Requirements in Pounds										
Dry Matter		768	2160		1215			837	3699	810
Energy (TDN)		352.64	1135.80		713.25			472.13	2086.51	456.90
Crude Protein		47.68	168.30		122.85			77.81	343.87	75.30
Calcium		1.28	5.40		3.60			2.17	9.59	2.10
Phosphorus		0.96	3.60		2.25			1.55	6.85	1.50

12-Month Requirements in Pounds

	Totals for Rations	Totals for Pastures	Totals for 12 Months
Dry Matter	3375	6114	9489
Energy (TDN)	1849.05	3368.18	5217.23
Crude Protein	291.15	544.66	835.80
Calcium	9.00	15.14	24.14
Phosphorus	5.85	10.86	16.71

Nutrients from Grass Forage

The available nutritional quality of pregrazed lead tillers of native cool and warm season grasses is closely related to the phenological stages of growth and development, which are triggered primarily by the length of daylight (Roberts 1939, Dahl 1995). The length of daylight increases during the growing season between mid April and 21 June and then decreases. All native cool and warm season grasses have adequate levels of energy throughout the growing season.

Native cool season grasses start early leaf greenup of vegetative carryover tillers in mid April and grow slowly until early May, reaching 59% of the leaf growth in height by mid May with crude protein levels above 16%. Most cool season grasses reach the 3.5 new leaf stage around early June at 73% of the leaf growth in height, contain levels of crude protein above 15% during early to mid June, reach 94% of the leaf growth in height by late June, and 100% of the leaf growth height by late July. Most cool season grasses reach the flower stage before 21 June. After the flower stage, crude protein levels begin to decrease below 15%. During the seed development stage, flower stalks reach 94% of the growth in height by late June and crude protein levels remain above 9.6% until mid July. The growth in height reaches 100% by late July when seeds are maturing and being shed. As the lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility decrease. During late July, crude protein levels drop below 8.0% and below 6.5% in late August (Whitman et al. 1951, Goetz 1963, Manske 2000c, 2008b). Crude protein levels of cool season secondary tillers increase above 9.6% during July and August to 13.2% in early September, decrease during September, and drop below 9.6% in early to mid October (Sedivec 1999, Manske 2008b) (figure 1). Phosphorus levels of lead tillers drop below 0.18% in late July, when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

Native warm season grasses start early leaf greenup of vegetative carryover tillers in mid May, have crude protein levels above 15%, reach 44% of the leaf growth in height by early June, containing crude protein above 13% during early to mid June. Most warm season grasses reach the 3.5 new leaf stage around mid June, reaching 85% of the leaf growth in height by late June and reach 100% of height by late July. Seed stalks begin to develop in mid June and reach the flower stage after 21 June with 12.2% crude protein. During the seed development stage, crude protein levels remain above 9.6% until late July when the flower stalks reach 91% of the growth in height. As the lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility decrease. During mid August, crude protein levels drop below 7.0%, seed stalks reach 100% of the growth in height by late August when the seeds are mature and being shed, and drop below 6.0% in crude protein by early September (Whitman et al. 1951, Goetz 1963, Manske 2000c, 2008b). Crude protein levels of warm season secondary tillers increase above 9.0% during August to 10.0% in early September, decreases during September, and drop below 9.6% in late September (Sedivec 1999, Manske 2008b) (figure 2). Phosphorus levels of lead tillers drop below 0.18% in late August, when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

Crude protein levels of upland sedges do not follow the same relationship with phenological growth stages as in cool and warm season grasses. Crude protein levels in upland sedges remain high through the flower and seed mature stages. Upland sedges grow very early and produce seed heads in late April to early May and crude protein remains above 9.6% until mid July. Crude protein levels decrease with increases in senescence and drop below 7.8% in early August but do not fall below 6.2% for the remainder of the growing season (Whitman et al. 1951, Manske 2008b) (figure 3). Phosphorus levels drop below 0.18% in mid May when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

The quality of grass forage available to grazing graminivores on grasslands of the Northern Plains is above 9.6% crude protein in the lead tillers of the cool and warm season grasses during mid May to late July. Upland sedges have crude protein levels above 9.6% during early May to mid July. The secondary tillers of the cool and warm season grasses have crude protein levels above 9.6% during mid July to late September or mid October.

The early greenup of rangeland grass in the spring is not from new seedlings but from vegetative carryover tillers that did not produce a seedhead during the previous growing season. Spring growth of carryover tillers depends both on carbohydrate reserves and on photosynthetic products from the portions of previous years leaves that overwintered without cell wall rupture and regreened with chlorophyll. Grass tiller growth and development depend, in part, on some carbohydrate reserves in early spring because the amount of photosynthetic product synthesized by the green carryover leaves and the first couple of early growing new leaves is insufficient to meet the total requirements for leaf growth (Coyne et al. 1995). Grass growth also requires that the tiller maintains adequate leaf area with a combination of carryover leaves and new leaves to provide photosynthetic product for growth of sequential new leaves. The total nonstructural carbohydrates of a grass tiller are at low levels following the huge reduction of reserves during the winter respiration period, and the carbohydrate reserves remaining in the roots and crowns are needed for both root growth and initial leaf growth during early spring. The low quantity of reserve carbohydrates are not adequate to supply the entire amount required to support root growth and also support leaf growth causing a reduction in active growth until sufficient leaf area is produced to provide the photosynthetic assimilates required for plant growth and other processes (Coyne et al. 1995). Removal of aboveground leaf material from grass tillers not yet at the three and a half new leaf stage deprives tillers of foliage needed for photosynthesis and increases the demand upon already low levels of carbohydrate reserves.

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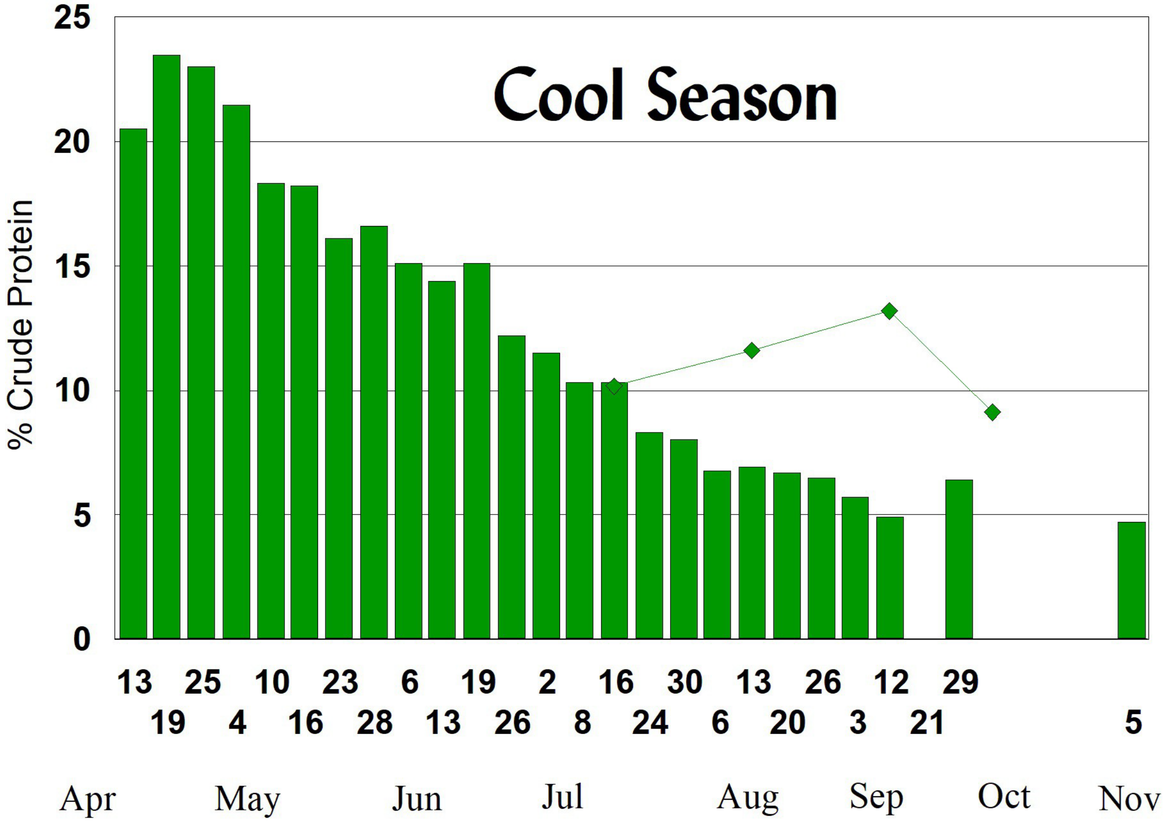

Fig 1. Mean percent crude protein of ungrazed native range cool season grasses in western North Dakota, data from Whitman et al. 1951 and secondary tiller data from Sedivec 1999.

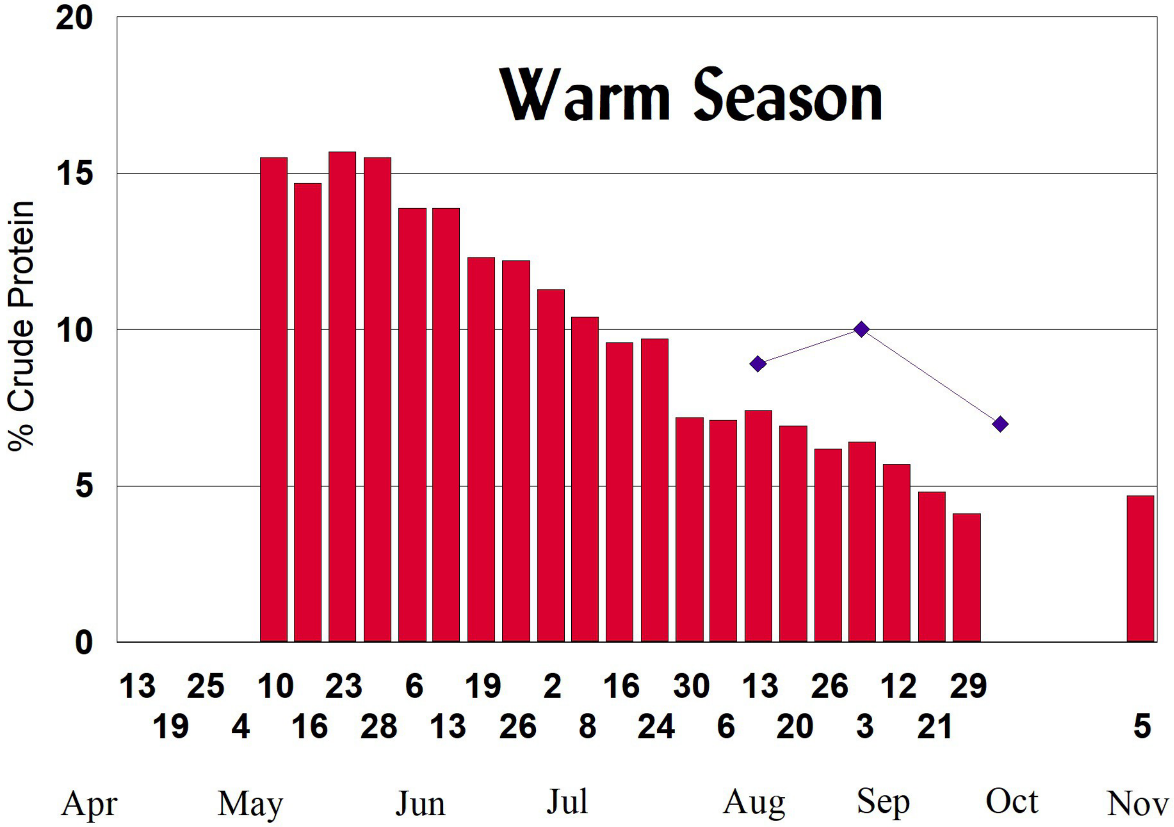

Fig 2. Mean percent crude protein of ungrazed native range warm season grasses in western North Dakota, data from Whitman et al. 1951 and secondary tiller data from Sedivec 1999.

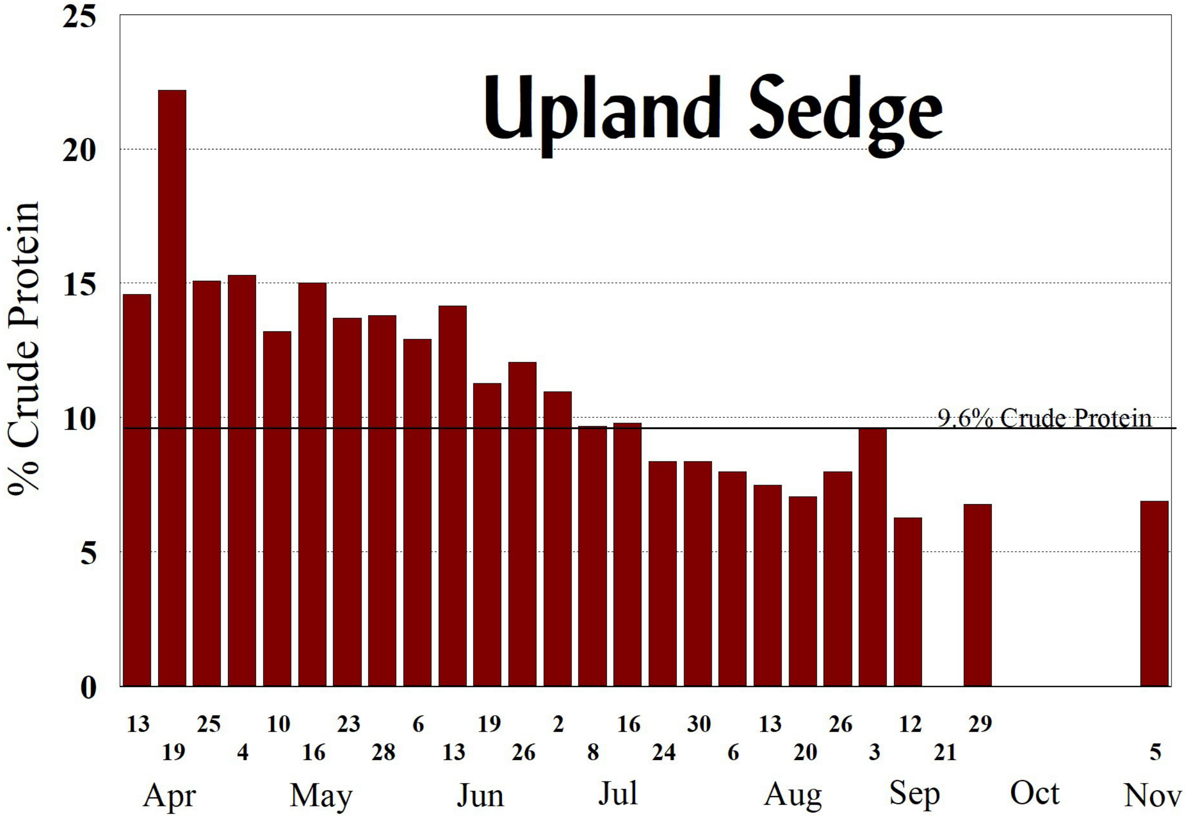

Fig 3. Mean percent crude protein of ungrazed native range upland sedges in western North Dakota, data from Whitman et al. 1951.

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Abiotic Components

Abiotic Climatic Factors

Grassland ecosystems are functioning units of coacting biotic organisms interactioning with the abiotic components. Grassland plant growth and development are regulated by the climatic factors. Long-term climatic factors determine the type of vegetation in that region. The most ecologically important abiotic climatic factors affecting grassland plant growth are light, temperature, water (precipitation), water deficiency, water stress, and the abiotic drought and fire environmental conditions.

Light

Light is necessary for plant growth because light is the source of energy for photosysthesis. Variations in quality, intensity, and duration of light affect plant growth. Light is necessary for photosynthesis, the process that converts light energy into chemical energy. The rate of photosynthesis varies with different wavelengths, but the quality (wavelength) of sunlight does not vary enough in a given region to have an important differential effect on the rate of photosynthesis. The intensity of sunlight (measurable energy) and duration of sunlight (length of day or photoperiod), however, do vary sufficiently to affect plant growth. Light intensity varies greatly with season and time of day because of changes in the angle of incidence of the sun's rays and the distance light travels through the atmosphere. Light intensity also varies with the amount of humidity and cloud cover because atmospheric moisture absorbs and scatters light rays. The greatest variation in intensity of light received by range plants results from the various degrees of shading from other plants. Because most range plants require full sunlight or very high levels of sunlight for best growth, shading can reduce or limit growth of range plants. Duration of sunlight (day-length period or photoperiod) is one of the most dependable cues by which plants time their activities in temperate zones. The buds or leaves of a plant contain sensory receptors, specially pigmented areas that detect day length and night length and can activate one or more hormone and enzyme systems that bring about physiological responses. The phenological development of rangeland plants is triggered primarily by changes in the length of daylight, although other environmental factors produce secondary effects and may cause slight variations in the pattern of phenological development. The tilt of the earth's axis in conjunction with the earth's annual revolution around the sun produces the seasons and changes the length of daylight, which increases from the beginning of the growing season until mid June then decreases to the end of the growing season. Photoperiod (day-length period) for a given date and locality remains the same from year to year (Odum 1971, Daubenmire 1974, Barbour et al. 1987).

Changes in day length (photoperiod) function as the timer and trigger that activates or stops physiological processes initiating growth and flowering and activates the process of hardening for resistance to low temperatures in the fall and winter. Vegetative growth is triggered by photoperiod and temperature (Langer 1972, Dahl 1995), and reproductive initiation is triggered primarily by photoperiod (Roberts 1939, Leopold and Kriedemann 1975, Dahl 1995) but can be slightly modified by temperature and precipitation (McMillian 1957, Leopold and Kriedemann 1975, Dahl and Hyder 1977, Dahl 1995). Cool- and warm-season plants respond to changes in photoperiod differently. Generally, most cool-season plants are long-day plants, and most warm-season plants are short-day plants. Long-day plants reach the flowering stage after exposure to a critical photoperiod and during the period of increasing daylight between the beginning of active growth and mid June, usually flowering before 21 June. Short-day plants are induced into flowering by day lengths that are shorter than a critical length and that occur during the period of decreasing day length after mid June, usually flowering after 21 June. Short-day plants are technically responding to the increase in the length of the night period rather than to the decrease in the day length (Weier et al. 1974, Leopold and Kriedemann 1975).

The tilt of the earth's axis in conjunction with the earth's annual revolution around the sun produces the seasons and changes the length of daylight in temperate zones. Dickinson (figure 1) has nearly uniform day and night lengths (12 hours) during only a few days, near the vernal and autumnal equinoxes, 20 March and 22 September, respectively, when the sun's apparent path crosses the equator as the sun travels north or south, respectively. The shortest day length (8 hours, 23 minutes) occurs at winter solstice, 21 December, when the sun's apparent path is farthest south of the equator. The longest day length (15 hours, 52 minutes) occurs at summer solstice, 21 June, when the sun's apparent path is farthest north of the equator. The length of daylight during the growing season (mid April to mid October) oscillates from about 13 hours in mid April, increasing to nearly 16 hours in mid June, then decreasing to around 11 hours in mid October (figure 1).

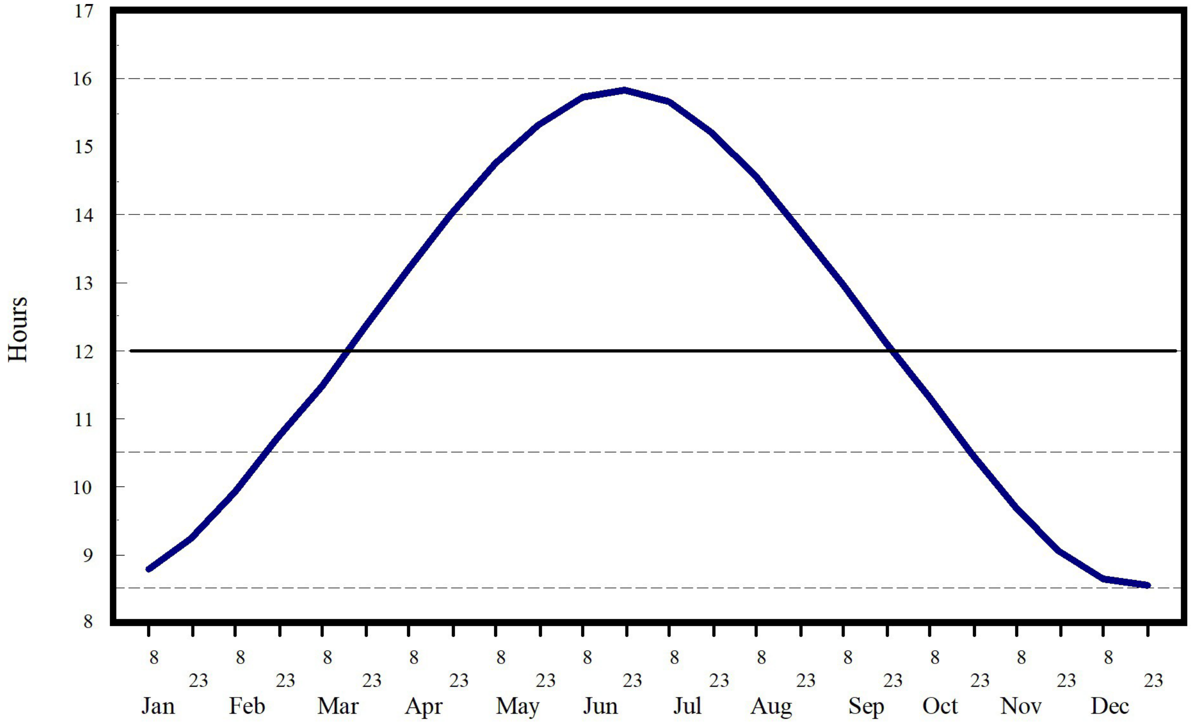


Figure. 1. Annual pattern of daylight duration at Dickinson, North Dakota.

Temperature

Temperature, an approximate measurement of the heat energy available from solar radiation, is an important factor because most plant biological activity and growth occur within only a narrow range of temperatures, between 32 F (0 C) and 122 F (50 C) (Barbour et al. 1987). High temperatures limit biological reactions because the complex structures of proteins are disrupted or denatured. Although respiration and photosynthesis can continue slowly at temperatures well below 32 F if plants are physiologically “hardened”, low temperatures limit biological reactions because water becomes unavailable when it is frozen and because available energy is inadequate.

Low temperatures define the length of the active growing season. The growing season for annually seeded plants corresponds approximately to the frost-free period, the number of days between the last day with minimum temperatures below 32 F (0 C) in the spring and the first day with minimum temperatures below 32 F (0 C) in the fall (Ramirez 1972). Perennial plants maintain physiological processes throughout the year. Winter dormancy in perennial plants is not total inactivity but reduced activity (Leopold and Kriedemann 1975). Perennial grassland plants can grow actively beyond the frost-free period if temperatures are above the level that freezes water in plant tissue and soil. Perennial plants begin active growth more than 30 days before the last frost in spring and continue growth after the first frost in fall; the growing season for perennial plants is considered to be between the first 5 consecutive days in spring and the last 5 consecutive days in fall with a mean daily temperature at or above 32 F (0 C), generally from mid April through mid October. Low air temperature during the early and late portions of the growing season and high temperatures after mid summer greatly limit plant growth (Jensen 1972).

Different plant species have different optimum temperature ranges. Cool-season plants, which are C_3 photosynthetic pathway plants, have an optimum temperature range of 50 to 77 F (10 to 25 C). Warm-season plants, which are C_4 photosynthetic pathway plants, have an optimum temperature range of 86 to 105 F (30 to 40 C) (Coyne et al. 1995).

Large fluctuations in seasonal and daily air temperature occur in the Northern Plains. The large diurnal change in temperature during the growing season, which has warm days and cool nights, is beneficial for plant growth because warm days increase the photosynthetic rate and cool nights reduce the respiration rate (Leopold and Kriedemann 1975).

Water (Precipitation)

Water, an integral part of living systems, is ecologically important because it is a major force in shaping climatic patterns and biochemically important because it is a necessary component in physiological processes (Brown 1995). Water is the principal constituent of plant cells, usually composing over 80% of the fresh weight of herbaceous plants. Water is the primary solvent in physiological processes by which gases, minerals, and other materials enter plant cells and by which these materials are translocated to various parts of the plant. Water is the substance in which processes such as photosynthesis and other biochemical reactions occur and a structural component of proteins and nucleotides. Water is also essential for the maintenance of the rigidity of plant tissue and for cell enlargement and growth in plants (Brown 1977, Brown 1995).

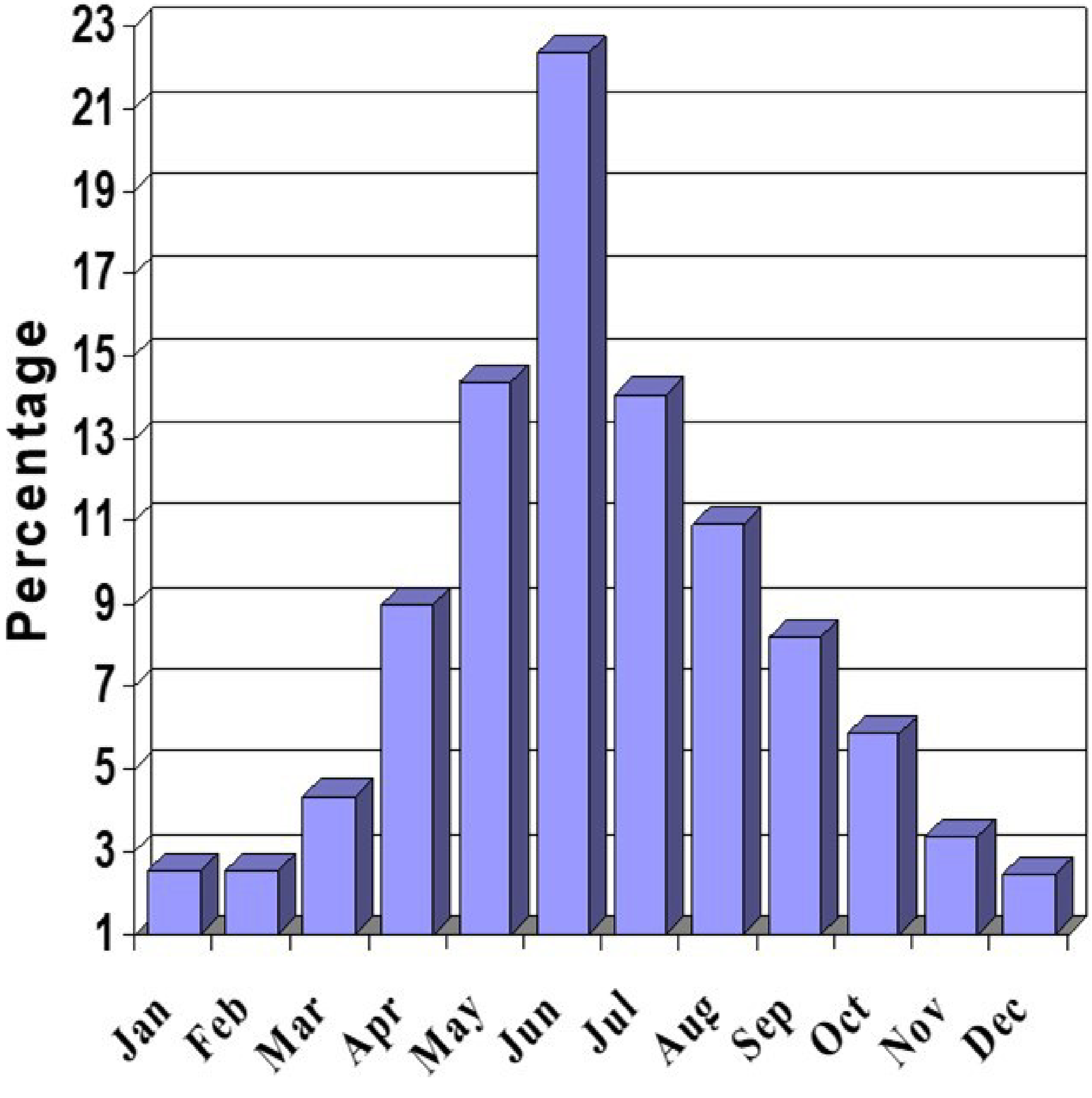
Precipitation Pattern

The current climate of the Northern Plains has existed for the past 5,000 years (Bluemle 1977, Bluemle 1991, Manske 1994, Bluemle 2000). The seasonal distribution of precipitation (Fig.) is classified as the Plains Precipitation Pattern (Humphrey 1962), in which most of the precipitation occurs during the growing season (85%) and the smallest amount occurs in winter (10%). Total precipitation for the 5-month nongrowing season of November through March averages less than 2.5 inches (63.5 mm) (15%) of precipitation. The greatest amount of precipitation occurs in spring and early summer (60%). The precipitation received in the 3-month period of May, June, and July accounts for over 50% of the annual precipitation, and June has the greatest monthly precipitation (22%).

Weather Air Mass Pattern

The weather of the Northern Plains is controlled by three major air masses that dominate at different times of the year (Redmann 1968). The Pacific air mass dominates the region from September through January, a period that is generally dry because the orographic effect of the Rocky Mountains causes a rain shadow as the air mass moves east. The mean monthly precipitation during this dry period is less than 1.0 inch (25.4 mm). The Polar air mass dominates the region from February through May, a period with mean monthly precipitation between 1.0 and 2.0 inches (25.4 mm and 50.8 mm). Throughout June, combinations of Gulf, Polar, and Pacific air masses mix and produce a relatively rainy period with a monthly precipitation average around 3.5 inches (88.9 mm). The summer months of July and August are dominated by the Gulf air mass, with little mixing of other air masses and a reduction of monthly precipitation to about 2.0 inches (50.8 mm), which comes generally in intermittent thunderstorms. The change from the dominance of one air mass to the next results in transition periods, which can vary annually. Differences in the transition periods contribute to the variation in conditions from year to year.

Seasonal Precipitation Distribution of the Plains Precipitation Pattern



Water Deficiency

The climatic conditions in the Northern Plains cause frequent periods when plants experience water stress. Rain deficiency periods in which 75% or less of the long-term mean precipitation is received are classified as droughts. Periods of drought conditions can last for a full year or a complete growing season, but water deficiency periods of one month are long enough to limit herbage production greatly. Water deficiency conditions during May, June, and July are not frequent. These months constitute the primary period of production for range plant communities. August, September, and October experience water deficiency conditions more than half the time and are not dependable for positive water relations. The water relations during this latter portion of the growing season limit range plant growth and herbage biomass accumulation (Manske 2011). Frequent late-season water deficiency limits shrub and tree growth more than grass growth.

Water Stress

Temperature and precipitation act together to affect the physiological and ecological status of range plants. The balance between rainfall and potential evapotranspiration determines a plant's biological water potential status. Precipitation-evapotranspiration levels interact and influence the rates of the carbon and nitrogen cycles. Evaporation rates are dependent on temperature: as average temperature decreases, evaporation rate decreases; as temperature increases, evaporation rate increases. The mixed grass and short grass prairie regions have greater evapotranspiration demand than precipitation. The tall grass prairie region has greater precipitation than evapotranspiration demand.

The native vegetation in the Northern Plains comprises a mixture of cool-season and warm-season species. The relationship between temperature and evaporation levels affects the ratio of cool-season to warm-season grasses in the plant species composition. The northern portion of the region has lower average temperature and lower evaporation rate; these conditions result in a higher percentage of cool-season species. The southern portion of the region has higher average temperature and greater evaporation rate; these conditions result in a higher percentage of warm-season species. A mixture of cool- and warm-season species is highly desirable because the herbage biomass production remains more stable over wide variations in seasonal temperature, precipitation, and evaporation levels.

During periods when rainfall is lower than evapotranspiration demand, a water deficiency exists. Under water deficiency conditions, the rate of water loss from transpiration exceeds the rate of water absorption by the roots, and plants undergo water stress. Water stress can vary from a small decrease in water potential (as in midday wilting on warm clear days) to the lethal limit of dessication. Although range plants have mechanisms that help reduce damage from water stress, water deficiency conditions lasting a month cause plants to experience water stress severe enough to reduce herbage production (Brown 1977, Brown 1995). The annual variation in temperature, precipitation, and evaporation affects the severity and duration of water deficiency, which in turn affect the levels of water stress.

Plant Water Stress

Plants experiencing water stress conditions respond at different inhibitory levels in relationship to the severity of the water deficiency. Early stages of water stress slow shoot and leaf growth. Leaves show signs of wilting, folding, and discoloration. Tillering and new shoot development are reduced, but root production may be increased. Senescence of older leaves is accelerated. Cell wall formation, cell division, and protein synthesis are reduced. As water stress increases, enzyme activity declines and the formation of necessary compounds slows or ceases. The stomata begin to close, and rates of transpiration and photosynthesis decrease. Respiration and translocation are substantially reduced as water stress increases. When water stress becomes severe, most functions nearly or completely cease and severe damage occurs. Leaf and root mortality induced by water stress progresses from the tips to the crown, its rate increasing with increasing stress. If water stress is prolonged or becomes more severe, the condition can be lethal. Plant death occurs when the meristems become dehydrated beyond the limits required to maintain cell turgidity and biochemical activity (Brown 1995).

Plants in water stress have limited growth and reduced photosynthetic activity. Plant vigor is decreased, carbohydrate storage is reduced, and root biomass is reduced. Plant height and herbage biomass accumulation are reduced. Leaf senescence increases and, as a result, nutritional quality of forage decreases. The rate of sexual reproduction is diminished as a result of a decrease in seed stalk numbers and height and a reduction in numbers of seeds in the seed heads. Rate of vegetative reproduction is reduced because the number of axillary buds and the number of secondary tillers decrease.

Basal cover is reduced because of mortality of entire plants or portions of plants, and open spaces in the plant community increase because of a decrease in plant numbers. The species composition shifts to an increase in species with advanced water-stress resistance mechanisms and a decrease in drought-susceptible species. Occurrence of some forbs and weedy species increases because of their ability to exploit the open spaces. Quantity and quality of wildlife habitat diminish. Livestock performance decreases because of the reductions in the quantity and quality of available forage, which in turn cause a reduction in milk production and a corresponding reduction in calf rate of gain and weaning weight. During extended periods of water stress, stocking rates generally need to be reduced.

Drought Conditions

Drought has been an irregular abiotic environmental factor on grasslands from their beginning, as has fire.

Periods with rainfall shortage are normal weather conditions for the Northern Plains. Long-term precipitation records (118 years) for western North Dakota show that a 6 month perennial plant growing season, mid April to mid October, rarely has adequate rainfall each month. Only 6% of the growing seasons occur without water deficiency, that's only 3 years in a 50 year period.

The average 6 month perennial plant growing season has 2 months with water deficiency (33%). This should be considered as the typical growing season for the Northern Plains. The frequency of water deficiency occurrence is not distributed evenly across the growing season months. Frequency of water deficiency has occurred 17% in April, 14% in May, 10% in June, 38% in July, 53% in August, 50% in September, and 47% in October.

Normal rainfall for an area is between 125% and 75% of the long-term mean (LTM), which is often determined for the growing season and for the year. In western North Dakota, normal rainfall occurs during 67% of the growing seasons, and 18% of the growing season have rainfall greater than 125% of LTM. Most of the growing seasons, 85%, receive rainfall at 75% or greater than the long-term mean.

Drought conditions occur during 15% of the growing seasons in western North Dakota and receive less than 75% of LTM, that's about 2 drought seasons every 13 years. No drought growing seasons have been back to back since 1892. Most of the growing seasons with drought conditions are considered to be moderate, with precipitation at less than 75% but greater than 50% of LTM. Moderate drought conditions occur during 12% of the growing seasons, or 1 moderate drought every 8 years.

Severe droughts are usually wide spread and everyone remembers them. Severe droughts have occurred during 3% of the growing seasons and receive rainfall at less than 50% of LTM, or about 1 severe drought every 29 years. Western North Dakota has experienced severe droughts during 1919, 1934, 1936, and 1988.

Livestock producers usually endure forage deficiency problems even during moderate droughts. Low rainfall is the most obvious detrimental factor. However, the additional factors of higher soil evapotranspiration rates, deteriorating soil structure, decreasing soil organism activity, and reduction of ecosystem health status all negatively affect forage production. If the reduction in rainfall were the only factor causing decreased forage production, the percent reduction in forage below normal levels would be the same percentage as the reduction in precipitation.

Forage production on grasslands managed with traditional or gimmicky grazing management practices is usually reduced by more than double the percent reduction in precipitation. The major cause for the quantity of reduction in forage production greater than the percent reduction in precipitation is the low quantity of available mineral nitrogen in the soil.

Wight and Black (1972) were able to determine that the minimum quantity of 100 lbs of available mineral nitrogen per acre was required in order to sustain forage production at the biological potential level for rangelands in the Northern Plains.

Wight and Black (1979) found that the precipitation use efficiency mechanism (lbs of herbage produced per inch of precipitation received) within rangeland grasses improved when soil mineral nitrogen was available at quantities of 100 lbs/ac or greater. Inhibitory deficiencies of mineral nitrogen in rangelands that had less than 100 lbs of available mineral nitrogen caused the weight of herbage produced per inch of precipitation received to be reduced an average of 49.6% below the weight of herbage production per inch of precipitation on the rangeland ecosystems that had 100 lbs/ac or greater of mineral nitrogen.

Two other internal grass growth mechanisms of the compensatory physiological processes that replace defoliated leaf and stem biomass and the asexual processes of vegetative reproduction that produce secondary tillers from axillary buds also require 100 lbs/ac of available mineral nitrogen to be properly activated.

The quantity of available mineral nitrogen in the soil also directly effect the rate of ecosystem recovery following a growing season with low rainfall. Traditionally managed rangelands generally have 50 to 60 lbs/ac of mineral nitrogen and require 1 full growing season with reduced stocking rates to recover from a moderate drought and require 2 growing seasons to recover from a severe drought.

Biologically effective management strategies that have 100 lbs/ac or greater of available mineral nitrogen require 1 growing season to recover from a severe drought but the ecosystem can recover without reducing stocking rate following a moderate drought.

Intact grassland soils (never plowed) are not deficient in nitrogen. Unbroken grassland soils contain between 3 to 8 tons, with most at 5 to 6 tons, of organic nitrogen per acre, which is not available for grass plant use. With this great quantity of organic nitrogen, intact grassland soils should never need the application of supplemental nitrogen. The organic nitrogen must be transformed into mineral nitrogen in order to be usable by grass plants. Soil microorganisms in the rhizosphere around perennial grass roots can transform organic nitrogen into mineral nitrogen. However, the rhizosphere microbes are achlorophyllous and cannot fix their own carbon energy.

Grass lead tillers fix surplus carbon energy during their vegetative growth stages between the 3.5 new leaf stage and the flower (anthesis) stage which occurs between 1 June and 15 July each year. This surplus carbon energy can be released from the grass tillers and exudated through the roots into the rhizosphere, to the soil microbes, if cattle grazing is specifically managed so the animals partially defoliate 25-33% of the aboveground leaf biomass on 60-80% of the lead tillers.

Drought conditions are going to come again, livestock producers should make some preparations. Manage the grazinglands to transform 100 lbs/ac of mineral nitrogen or greater in the soil, and store about 12% of the hay forage as silage during each normal year in order to have adequate feed during the drought year to keep the good genetics in the cow herd intact and permit the grassland ecosystem to recover during the following growing season.

Abiotic Fire on Grasslands

Fire has been a recurrent abiotic environmental factor on grasslands from their beginning, as has drought.

Many grassland ecologists have observed that the occurrence of fire was the force that prevented intrusion of shrubs and trees into grasslands (Weaver 1954, Humphrey 1962, Daubenmire 1974, Stoddart, Smith, and Box 1975, Wright and Bailey 1982). This observational concept is almost universally accepted among modern grassland ecologists. However, the processes of how fire prevents woody species encroachment and how fire can restore degraded grassland ecosystems have not been clearly explained.

Grass plants, soil organisms, and large grazing graminivores have developed complex symbiotic relationships. Grass plants have internal physiological growth mechanisms, rhizosphere microorganisms perform ecosystems biogeochemical processes, and all of these mechanisms and processes are activated by coordinated partial defoliation by grazing graminivores (Manske 2018).

When grazing management is not coordinated with grass phenological growth stages, the rhizosphere microbe biomass decreases, causing the quantity of available mineral nitrogen and other major and minor essential elements to decrease, which reduces the quantity and quality of grass forage, that causes cow milk production to decrease and calf weight gain to drop below biological potential. The grassland ecosystem functionality is greatly diminished and the ecosystem mechanisms and processes are degrading. Grass density decreases that increases bare spaces making room for weedy and undesirable grasses, forbs, and woody shrubs and trees to encroach resulting in deteriorated grassland ecosystems.

Fire causes damage to all plants and severely removes all or nearly all of the aboveground plant material of grasses and forbs, the aboveground parts of shrubs and trees may not be totally consumed but most will be top killed. Of the fifty three major invasive woody species of the Northern Plains, only five usually suffer total plant kill by fire because they lack vegetative buds (Manske 2019). Most, 48 (90.6%) of the invasive woody species have vegetative buds. The replacement of fire removed plant material must develop from vegetative buds and stored root carbohydrate reserves. The replacement growth after a fire occurs at greatly reduced rates because of the complete dependence on reduced quantities of stored carbohydrates (Coyne et al. 1995). Top kill of plants damages the leaves that prevents contributions of carbohydrates for growth of vegetative buds and replacement plant material.

Fire cannot remove woody species that can reproduce by vegetative buds from grasslands. Fire cannot restore degraded grassland ecosystems because fire does not activate the internal physiological growth mechanisms of grass plants. Fire does not activate the ecosystem biogeochemical processes. Fire cannot increase the quantity and quality of grass forage to improve cow and calf performance. The fundamental problems of degraded grassland ecosystems of weak nutrient resource uptake, reduced water use efficiency, nonfunctional compensatory physiological mechanisms, impaired vegetative reproduction by tillering, and diminished biogeochemcial processes remain in deteriorated grassland ecosystem following repeated fire treatments. Fire does not improve grassland ecosystems biologically or ecologically, and fire cannot replace coordinated partial defoliation by grazing graminivores (Manske 2018).

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Abiotic Essential Elements

Major Essential Elements

Perpetuation of life on earth requires that the abiotic major and minor essential elements be reused over and over. Essential elements are required for life to exist by ensuring growth and development of organisms and the maintenance of all life functions. Recycling of the essential elements in grassland soils is performed by rhizosphere microorganisms. The major essential elements required in very large amounts by all animals and plants are: carbon (C), hydrogen (H), nitrogen (N), and oxygen (O). The source of these major essential elements is not the soil but from air and water (Manske 2018d). A major essential element is not part of the grassland ecosystem until it is incorporated into an ecosystem organism. The organic forms of the major essential elements are stored in the soil organic matter SOM (table 1).

Solar radiant energy from the sun is the ecosystem input source for energy. Solar energy reaching the earth's atmosphere that is facing the sun is about 1,365 Watts m^{-2} (Working Group I 2007) with greater amounts at the equator than at the north and south latitudes. Solar energy is captured and stored by autotrophic plants through the chemical process of photosynthesis in chloroplasts where inorganic major essential elements of carbon, hydrogen, and oxygen are synthesized into organic compounds of carbohydrates (CH_2O) (Manske 2018d).

Atmospheric carbon dioxide gas (CO_2) is the ecosystem input source for carbon. Atmospheric carbon dioxide composes about 0.0412% of the gasses in the atmosphere and exists at concentrations of around 385 to 412 ppm (Anonymous 2021a). Carbon dioxide can be obtained directly from air by autotrophic plants in the production of carbohydrates. Carbon reactions in soil produce carbonates and bicarbonates that are readily soluble and available to higher plants. Organic carbon compounds are stored in the soil organic matter. Increases in soil organic carbon SOC improve nutrient storage, increase water holding capacity, and enhance aggregation (Manske 2018d).

Soil water (H_2O) is infiltrated precipitation water and is the ecosystem input source for plant water, hydrogen ions (H+) and hydroxyl ions (OH-). Soil air contains higher concentrations of water vapor (H_2O) than the atmosphere. Hydrogen ions (H+) and hydroxyl ions (OH-) are released into the soil during the early stages of soil organic matter decomposition (Manske 2018d).

Atmospheric nitrogen gas (N_2) is the original input source for ecosystem nitrogen. Atmospheric nitrogen (N_2) composes about 78.084% of the gasses in the atmosphere. The bonds of atmosphere nitrogen are strong and make N_2 gas inert to most higher organisms. The high temperature of a lightning bolt at 50,000 F (28,000 C) can break these nitrogen bonds. Free nitrogen atoms in the air bond with oxygen to create nitrogen oxides (NO, NO_2), which dissolve in water to form ammonium (NH_4) and nitrate (NO_3) in soil. The global lightning production of nitrogen atoms is estimated at 1 to 20 Tg N yr^{-1} (Tg=Tera trillion 10^{12} g) (Anonymous 2021b) which is, in the temperate zone, about 5 to 6 pounds of nitrogen per acre per year (Brady 1974, Gibson 2009). A net accumulation of 2 pounds of nitrogen per acre per year results in a soil with 5 tons of nitrogen per acre in 5000 years. Most of the nitrogen in soils is stored in the soil organic matter SOM as organic nitrogen that is unavailable to plants. Northern Plains intact soils contain around 3 to 8 tons of organic nitrogen per acre. Rhizosphere microorganisms mineralize organic nitrogen into inorganic nitrogen in forms of ammonium (NH_4) and nitrate (NO_3) which are available to plants and are the source of nitrogen for plant growth (Manske 2018d).

Atmospheric oxygen gas (O_2) is the ecosystem input source for oxygen. Atmospheric oxygen composes about 20.946% of the gases in the atmosphere. Oxygen can be obtained directly from the air by autotrophic plants. Oxygen is usually at lower concentrations in soil air. Respiration of plant roots can directly use the oxygen in soil air. Aerobic decomposition of organic residue by microbes can directly use the oxygen in soil air. Oxidation of organic carbonaceous compounds produces carbon dioxide (CO_2) that is emitted from soils into the atmosphere. Plant photosynthetic rates during the growing season remove greater quantities of carbon dioxide from the atmosphere than the quantities of CO_2 emissions (Manske 2018d).

Minor Essential Elements

The minor essential elements are the macronutrients required in large amounts and the micronutrients required in very small amounts. The source of all the minor essential elements is weathered soil parent material. The minor essential elements are stored in the soil organic matter as unavailable organic forms or as ions adsorbed by colloidal complexes and are biologically and chemically immobilized, respectively. While in these stable forms, the minor essential elements are not subjected to potential losses through volatilization or leaching movement (Legg 1975, Gibson 2009). The immobilized minor essential elements are made available through the ecosystem biogeochemical cycles performed by rhizosphere microorganisms (McGill and Cole 1981, Cheng and Johnson 1998, Manske 2012, 2014). The quantity of available minor essential elements is determined by the recycling rates of soil organic matter decomposition and mineralization that are directly regulated by the biomass of active rhizosphere microorganisms (Manske 2018d).

Animals and plants require large amounts of the same macronutrients: potassium (K). calcium (Ca). phosphorus (P), magnesium (Mg), and sulfur (S). Animal require an additional macronutirent: sodium (Na) and require chlorine (Cl) as a macronutrient. Warm season plants and cacti use some sodium (Na). Animals and plants require very small amounts of the same micronutrients or trace elements: iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), and nickel (Ni). Animals require additional micronutrients: iodine (I), cobalt (Co), selenium (Se), and chromium (Cr). Plants require an additional micronutrient: boron (B), and require chlorine (Cl) as a micronutrient. A few plants and rhizobia use some cobalt (Co) (table 1) (Manske 2018d).

Management practices that permit the use or loss of greater quantities of essential elements than the quantities of replacement essential elements captured cause grassland ecosystems to degrade. The single most important factor that permits the capture of greater quantities of replacement essential elements than the quantities used or lost is a large biomass of active soil microorganisms (Coleman et al. 1983, Schimel, Coleman, and Horton 1985, Cheng and Johnson 1998). The soil microorganisms are the renewable portion of grassland natural resources.

Aggradation of grassland ecosystems occurs when beneficial management practices cause increased quantities of labile (readily available) simple carbon chain energy from grass lead tillers at vegetative growth stages to be exudated (released) through the roots into the rhizosphere providing the limiting nutrient necessary for microorganism biomass to increase (Anderson et al. 1981, Curl and Truelove 1986, Whipps 1990, Hamilton and Frank 2001, Manske 2011). The resulting increased biomass of soil microorganisms are able to decompose and mineralize greater quantities of the soil organic matter producing greater quantities of essential elements in plant available mineral (inorganic) forms (Coleman et al. 1983, Klein et al. 1988, Bird et al. 2002, Burrows and Pfleger 2002, Rillig et al. 2002, Driver et al. 2005). The increased quantities of available essential elements provide for increased production of plant herbage biomass and increased livestock weight production (Manske 2008b).

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Table 1. Essential Elements Required by Animals and Plants.

Major Essential Elements required by animals and plants

- Carbon (C), Hydrogen (H), Nitrogen (N), Oxygen (O)

Minor Essential Elements

- Macronutrients required by animals and plants
- Potassium (K), Calcium (Ca), Phosphorus (P), Magnesium (Mg), Sulfur (S)
- Macronutrients required by animals
- Sodium (Na), Chlorine (Cl)

- Micronutrients required by animals and plants
- Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu)
- Molybdenum (Mo), Nickel (Ni)
- Micronutrients required by animals
- Iodine (I), Cobalt (Co), Selenium (Se), Chromium (Cr)
- Micronutrients required by plants
- Boron (B), Chlorine (Cl)

Blue elements required by both animals and plants, Red elements required by animals, Green elements required by plants.

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Abiotic Soil Formation

Parent Material

The unglaciated region of the Northern Plains is part of a large geologic depression, which has been filled over a period of 515 million years with accumulations of sedimentary rocks deposited in off-shore shallow seas and in near-shore marine environments or by running water on floodplains or deltas. For about the last 5 million years, running water and wind have been eroding the generally flat-lying sedimentary deposits in the unglaciated region. These erosional forces have been selective in their action because hard, relatively resistant sandstone, limestone, scoria, chert, or other erosion-resistant materials were present in some of the sedimentary deposits and have remained as protective caps, while the soft, weakly consolidated, less resistant silt and clay layers have been easily washed or blown away. The landforms that have resulted from uneven sediment removal are gently rolling to hilly plains intermingled with buttes, which have flat tops and steep slopes. Over the last 600,000 years, badlands topography has developed near some streams and rivers from erosional forces that accelerated sediment removal when glacial ice blocked the northward flow of the drainage systems. The diverted routes to the east were shorter and steeper, and the water flowing in the drainage systems caused deep rapid erosion that resulted in badlands landforms (Hunt 1974, Bluemle 1977, Trimble 1990, Bluemle 1991, Bluemle 2000).

Soil Development

Soils in the unglaciated region have been developing from weathered sedimentary deposits of soft shale, siltstone, and sandstone. Soil formation is a long, slow, continuous process. Temperatures and precipitation levels of the area have been important in the development of the regional soils. The climate has determined the type of vegetation and the amount of annual growth, which, in turn, have influenced the amount of soil organic matter accumulated. Temperature affects the rate of oxidation of organic matter. Higher temperatures promote rapid oxidation of organic matter, and soils in regions with long periods of high temperatures contain little organic matter. Little or no oxidation of organic matter occurs in frozen soil. Organic matter has accumulated in the soils in the Northern Plains because the climate has cold periods during which little chemical activity takes place. In most years, soils in the unglaciated region have frost penetration to a depth of 3 to 5 feet for a period of approximately 120 days (Larson et al. 1968), a condition that contributes to soil organic matter accumulation. The dark surface layer of most soils in the region has an accumulation of 2 to 5% organic matter (Larson et al. 1968, Wright et al. 1982).

Temperature and precipitation have influenced the amount and kinds of physical and chemical weathering of the region's parent material. High temperatures and high precipitation have encouraged rapid weathering and clay formation during the summer, while low temperatures during fall, winter, and early spring have caused cracks, fissures, and breaks in the parent material and developing soil as a result of the expansion and contraction forces of frost.

Precipitation level has influenced the amount of water in the soil. The amount of water that has entered the soil has not been the same as the precipitation level, and the amount of soil water has not been the same on all parts of the landscape. The amount of soil water has been less than the amount of precipitation received in areas that have had rain run off, and the amount of soil water has been greater than the amount of precipitation received in areas that have had rain run in. The amount of soil water present has affected the rate of leaching. The depth of the downward movement of the water has not been uniform for the soils on different topographic positions on the landscape.

Soil water has dissolved calcium carbonate (lime), soluble salts, exchangeable sodium, and clay particles from the upper horizons of the soil and has moved them downward into a lower horizon. The amount of these dissolved materials in the soil profile has been dependent on the amount present in the weathered parent material. The depth to which they have been moved has varied with the amount of soil water. The layer where the dissolved material has accumulated indicates the approximate average depth of downward water movement. The depth of the accumulation layer decreases when the precipitation decreases. Soils with a high lime content have developed a layer of natural cement (hardpan) that restricts plant root penetration. Soils high in soluble salts and/or exchangeable sodium have developed accumulation layers containing sufficient amounts of these chemicals to impair plant growth. Soils high in soluble salts have developed into saline soils; soils high in exchangeable sodium have developed into sodic soils; and soils high in both have developed into saline-sodic soils (Omodt et al. 1968, Soil Survey Staff 1975, Foth 1978).

Soil water has also dissolved clay particles and moved the clay downward. When the soil water with dissolved clay has hit areas of dry soil, the water has been withdrawn and the clay particles have been deposited. Over time this clay film layer has built up to form what is called an argillac horizon. Low amounts of argillac horizon in a soil can be beneficial because the clay helps increase the amount of water and nutrients stored in that zone; however, when the clay accumulation becomes great, the effects can be detrimental because water movement and plant root penetration are severely restricted. Soils that have a well-developed argillac horizon are called clay-pan soils (Omodt et al. 1968, Soil Survey Staff 1975, Foth 1978).

The depth of the layer where the dissolved material accumulates is very important because it determines the thickness of the plant growth medium; the soil above the layer of accumulation holds the nutrients and soil water needed to sustain plant life. Shallow soils restrict plant growth. The depth of the accumulation layer decreases westward with the reduction in precipitation and ranges from 6 inches to 4 feet. Most soils in western North Dakota have formed the accumulation layer between 15 and 24 inches below the soil surface (Larson et al. 1968, Omodt et al. 1968, Soil Survey Staff 1975, Foth 1978, Wright et al. 1982).

Abiotic Soil Characteristics

Soil development is effected by climate, parent material, topography, living organisms, and time (Brady 1974). The main climatic factors that affect soil development are temperature and precipitation. Climate determines the type and rate of weathering that occurs. The rates of biogeochemical processes in soil are effected by soil temperature and soil moisture. Climate determines the type of native vegetation and the quantity of biomass production. There is a relationship between the type of native vegetation and the kind of soil that develops. Increases in soil moisture, increase the biomass production and tend to increase organic content of soils. Increases in soil temperature, increase the rate of decomposition and tend to decrease organic content of soils (Brady 1974).

The Northern Plains has a continental climate with cold winters and hot summers. Mean air temperatures increase from north to south changing from about 35 - 40 F (1.7 - 4.4 C) in the north to about 48 - 51 F (8.9 - 10.6 C) in the south. Most of the precipitation occurs during the early portion of the growing season. Total annual precipitation fluctuates greatly from year to year. Periods of water deficiency during the growing season occur more frequently than growing seasons without deficiencies. Drought conditions are common. Mean annual precipitation increases from west to east and increases from north to south. In the northern portion, precipitation ranges from about 12 inches (304.8 mm) in the west to about 24 inches (609.6 mm) in the east. In the southern portion, precipitation ranges from about 14 inches (355.6 mm) in the west to about 32 inches (812.8 mm) in the east.

Evapotranspiration affects the quantity of moisture in the soil and the duration infiltrated water remains available for plant growth. The potential evapotranspiration for most of the Northern Plains is greater than annual precipitation. Potential evapotranspiration demand increases from north to south, and increases from east to west. Along the eastern edge of the Northern Plains, the precipitation is greater than potential evapotranspiration during most years. The region also has several local areas where the combination of stored soil water, precipitation, plus water runin is greater than evapotranspiration. Subirrigated soils where the rooting zone is moist for most of the growing season would be comparable to conditions with greater precipitation than evapotranspiration.

The properties of the parent material that affect soil development include texture and structure, and chemical and mineral composition. The texture and structure of parent material varies from fine to coarse and is related to the type of source material and the degree of weathering. The texture of the parent material determines the texture of the soil and the relative content of clay, silt, sand, and gravel. The texture of the soil controls the downward movement of water. The chemical and mineral composition of the parent material strongly influences the growth of the native vegetation and determines the effectiveness of the weathering forces. Parent material influences the quantity and type of clay minerals that develop (Brady 1974). The parent material on the Northern Plains is eroded Tertiary fluvial sedimentary deposits, unsorted glacial till, sorted glacier related deposits of outwash and lake sediments, and wind deposited sand and silt.

Landform topography modifies soil development by influencing the quantity of precipitation absorbed and retained in the soil, determines aspect to solar radiation, and influences the rate of soil removal by erosion. Water, organic matter, mineral matter, and soluble salts move down slope, whether over the surface or internally. The steeper the gradient, the greater the movement. Soil temperature changes with slope aspect. Increases in soil temperature, increase evapotranspiration and decomposition rates. Upper slope soils tend to have lower soil moisture, less organic matter, and thinner horizon development than lower slope soils from similar parent material (Brady 1974).

Living organisms (including plants, animals, and soil microorganisms) affect soil development by influencing organic matter accumulation, profile mixing, nutrient cycling, and structural stability. The source of soil organic matter is the dead tissue and waste from organisms, decomposition is performed by soil organisms, nutrient cycles are complex processes involving living organisms, burrowing critters mix soil material, and soil aggregation is a result of soil organism secretions (Brady 1974).

Time is required for soils to develop and mature. However, soils do not all develop at the same rate. Conditions that increase soil development are warm humid climate, parent material highly permeable by water, unconsolidated material, low lime content, depression or level topography, good drainage, and forest vegetation. Conditions that retard soil development are cold dry climate, parent material not permeable by water, consolidated material, high lime content, steeply sloping topography, poor drainage, and grassland vegetation (Brady 1974). Some very old soils in the Northern Plains show little or no evidence of horizon development because they exist in dry regions, on steep, actively eroding slopes where the rate of soil removal is as great or greater than the rate of soil development.

The soils that are developing in the Northern Plains fit into the order classification descriptions of Mollisols, Aridisols, and Entisols.

Mollisols are mineral soils that develop under grassland vegetation with a thick mollic epipedon that is “soft”, high in organic matter, and dark colored. The limited leaching results in a high base saturation with a concentration of positively charged exchangeable cations other than hydrogen. Most Mollisols in the Northern Plains have, or are developing, an argillic (clay) layer in an upper subhorizon and have an accumulation of calcium carbonate (lime) at some level of the profile (Soil Survey Staff 1975).

Aridisols are mineral soils that develop in aridic (dry) or torric (hot and dry) climates with a thin ochic epipedon that is low in organic matter and light colored. Soil water is not available to plants for long periods during the growing season. In the Northern Plains, the Aridisols have an argillic (clay) layer in an upper subhorizon and as a result of limited leaching, soluble salts, like calcium carbonate, accumulate in a zone that marks the average depth of moisture penetration (Soil Survey Staff 1975).

Entisols are mineral soils that show little or no evidence of horizon development and have a thin ochic epipedon that is low in organic matter and light colored. In the Northern Plains, considerable retardation of soil development produces Entisols where dry and/or salty medium to fine textured sediments with sparse grass or shrub vegetation are located on gentle to steep, actively eroding slopes with the rate of soil removal as great as the rate of soil development, or where coarse textured, well sorted, wind deposited sand with low water holding capacity and thin grass vegetation become dry and are easily moved by wind (Soil Survey Staff 1975).

Classification of soils into principal suborders is based on differences caused by climate and associated native vegetation. The biological processes in soil are effected by soil temperature and soil moisture. The different climatic characteristics important in soil development are separated into specific soil temperature regimes and soil moisture regimes.

The Northern Plains has two soil temperature regimes based on mean annual soil temperature. The mean annual soil temperature is considered to be the mean annual air temperature plus 1.8 F (1 C) (Soil Survey Staff 1975). The Frigid soil temperature regime has mean annual soil temperatures of less than 47 F (8 C). The Mesic soil temperature regime has mean annual soil temperatures higher than 47 F (8 C) and lower than 59 F (15 C) (Soil Survey Staff 1975). The separation between the Frigid and Mesic soil temperature regimes occurs along a wide irregular belt that extends eastward from central Wyoming along its north border with Montana and continues to north central South Dakota just south of its north border with North Dakota, then extends at a southeasterly diagonal to about the center of South Dakota’s east border with Minnesota, and then extends at a northeasterly angle to the boundary of the Oak Forest.

Soil moisture regimes are based on the soil moisture conditions in the soil. The Northern Plains has four north-south zones of soil moisture regimes that increase in soil moisture from west to east. The soils in the Aridic and Torric soil moisture regime, typically of arid climates, are dry in all parts for more than half the time and the soils are never moist for as long as 90 days during the growing season (Soil Survey Staff 1975). The soils in the Ustic soil moisture regime, typically of semi arid climates, are dry in some or all parts for 90 or more days in most years, but not dry in all parts for more than half the time, and are not dry for as long as 45 days during the 4 months that follow the summer solstice in 6 or more years out of 10 years (Soil Survey Staff 1975). The soils in the Udic soil moisture regime, typically of sub humid climates, are not dry for as long as 90 days. During the summer, the amount of stored moisture plus rainfall is approximately equal to or exceeds the amount of evapotranspiration (Soil Survey Staff 1975). The soils in the Perudic soil moisture regime, typically of humid climates, are rarely dry. During the summer, the precipitation is greater than the evapotranspiration (Soil Survey Staff 1975).

The combination of four soil moisture regimes (Aridic, Ustic, Udic, and Perudic) and two soil temperature regimes (Frigid and Mesic) results in eight distinct soil moisture-temperature regimes in the Northern Plains. The soils in the Aridic-Frigid soil moisture-temperature regime are primarily Aridic Borolls (arid cool Mollisols) and Torriorthents (hot dry recently eroded medium to fine textured Entisols) and support vegetation of short grasses with some mid grasses. The soils in the Ustic-Frigid soil moisture-temperature regime are primarily Typic Borolls (semi arid cool Mollisols) and support vegetation of mid and short grasses. The soils in the Udic-Frigid soil moisture-temperature regime are primarily Udic Borolls (sub humid cool Mollisols) and support vegetation of mid grasses with some tall grasses. The soils in the Perudic-Frigid soil moisture-temperature regime are primarily Aquolls (humid cool Mollisols that are saturated and absent of oxygen at times for unknown lengths) and support vegetation of tall grasses. The soils in the Aridic-Mesic soil moisture-temperature regime are primarily Argids (arid warm Aridisols with thin horizons, dry for long periods, and have a clay layer) and Aridic Ustolls (arid warm Mollisols) and support vegetation of short grasses. The soils in the Ustic-Mesic soil moisture-temperature regime are primarily Ustipsamments (semi arid warm Entisols that are well sorted wind deposited sands) and Typic Ustolls (semi arid warm Mollisols) and support vegetation of mid and short grasses with lower topographic slopes supporting tall grasses. The soils in the Udic-Mesic soil moisture-temperature regime are primarily Udic Ustolls (sub humid warm Mollisols) and support vegetation of mid grasses and tall grasses. The soils in the Perudic-Mesic soil moisture-temperature regime are primarily Udolls (humid warm Mollisols that do not have a calcium carbonate layer) and support vegetation of tall grasses.

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Vegetation of the Northern Plains

Native Vegetation Types

Development of plant communities and vegetation types is effected by the climatic characteristics of temperature, precipitation, and evapotranspiration demand; the soil characteristics of texture, structure, and chemical and mineral composition; and the landform topographic characteristics of slope, aspect, and elevation. Vegetation of the Northern Plains separates into 10 grassland vegetation types and 7 grassland with woodland or forest vegetation types. The vegetation of the Northern Plains map (figure 1) developed by Dr. W.C. Whitman (Barker and Whitman 1989) is a compilation of information from several sources supplementary to the basic map of potential natural vegetation by Kuchler (1964). Modifications to vegetation type designations, distributions, and boundaries were conflated into the base map from state vegetation maps for Montana (Ross and Hunter 1976, Hacker and Sparks 1977), Nebraska (Kaul 1975, Bose 1977), North Dakota (Shaver 1977), South Dakota (Baumberger 1977), and Wyoming (Shrader 1977). Vegetation type designations and distributions from scientific papers were added for Canada (Clarke, Campbell, and Campbell 1942; Moss and Campbell 1947; Coupland and Brayshaw 1953; Coupland 1950, 1961). A new concept of a plains rough fescue mixture along a portion of the northern border of North Dakota was introduced to the map details by Whitman and Barker (1989) (Manske 2017).

No living plant species are known to have originated in the Northern Plains. All plant species considered to be native to the Northern Plains originated and developed in other regions and sometime later migrated into the Northern Plains. The plant communities and vegetation types, however, are relatively young and began development in place about 5,000 years ago when the current climate with cycles of wet and dry periods began. Nomenclature of plants in the vegetation types of the Northern Plains followed Flora of the Great Plains (1986) in Barker and Whitman (1989) and, in addition, nomenclature of grass plants follows Flora of North America (2003, 2007) in this report.

Tall Grass Prairie

The Tall Grass Prairie, Bluestem-Switchgrass-Indiangrass Type, exists on the eastern margin of the Northern Plains Grasslands and extends from southern Manitoba through eastern North and South Dakota and western Minnesota southward into northwestern Iowa and northeastern Nebraska to the Platte River. The physiography of the region consists of the Manitoba Plain and the Red River Valley Plain of the Small Lakes Section and extends into the Dissected Till Plains Section of the Central Lowland Province. The climate is humid with evapotranspiration lower than precipitation. The soil moisture regime is Perudic and the soil temperature regime is Frigid in the north and Mesic in the south. The soils are primarily Aquolls in the north and Udolls in the south. The major grasses of the Bluestem-Switchgrass-Indiangrass Type of the Tall Grass Prairie are big bluestem, porcupinegrass, switchgrass, prairie dropseed, and indiangrass. Cool-season grass species increase towards the northern portions and warm-season grass species increase towards the southern portions. Big bluestem occupies the lower slopes and subirrigated soils in the north and increases in dominance in the south. Prominent forbs are prairie clover, tall blazing star, large beardtongue, stiff sunflower, scurf pea, white prairie aster, white sage, prairie goldenrods, and violets. Major shrubs are leadplant, white spiraea, wild roses, western snowberry, and willows. Most of this vegetation type has been converted to cropland, and only fragments of tall grass prairie vegetation remain. Plant communities with tall grass species exist in several other vegetation types where near equivalent environmental conditions develop from combinations of precipitation, stored soil water, and water runin that are greater than evapotranspiration.

Mesic Mixed Grass Prairie

The Mesic Mixed Grass Prairie, Wheatgrass-Bluestem-Needlegrass Type (figure 1), exists between the Tall Grass Prairie on the east and the Mixed Grass Prairie on the west and extends from east central Saskatchewan and southwestern Manitoba through east central North and South Dakota and east central Nebraska to the Platte River. The physiography of the region consists of the Saskatchewan Plain and the Glaciated Plains (Drift Prairie) of the Small Lakes Section of the Central Lowland Province and extends into the eastern portion of the High Plains Section of the Great Plains Province. The climate is sub humid with evapotranspiration greater than precipitation over most of the area except for subirrigated soils and topographic slope positions with water runin. The soil moisture regime is Udic and the soil temperature regime is Frigid in the north and Mesic in the south. The soils are primarily Udic Borolls in the north and Udic Ustolls in the south. The major grasses of the Wheatgrass-Bluestem-Needlegrass Type of the Mesic

Mixed Grass Prairie are western wheatgrass, thickspike (northern) wheatgrass, little bluestem, porcupinegrass, needle and thread, and green needlegrass. Cool-season grass species increase towards the northern portions and warm-season grass species increase towards the southern portions. The needlegrasses and thickspike wheatgrass increase in the north. Little bluestem increases in the south. Prominent forbs are white prairie aster, scurf peas, prairie coneflower, purple coneflower, milkvetches, dotted blazing star, white sage, soft goldenrod, curlycup gumweed, hairy golden aster, and stiff sunflower. Major shrubs are wild roses, western snowberry, silverberry, leadplant, white spiraea, and willows. Plant communities change with topographic position. Wetland communities develop in nearly concentric rings around depressions. The salt-affected "pot holes" support saline plant communities. Wet meadow communities develop on subirrigated soils. Upland communities develop on well drained soils and xeric communities develop on shallow soils. Kentucky bluegrass and western snowberry communities have greatly increased in this region as a result of high stocking rates and too early of grazing starting dates.

Mixed Grass Prairie

The Mixed Grass Prairie has a high mid grass component with some short grasses and some tall grasses present and is separated into three vegetation types based on differences resulting from soil texture and soil temperature regime.

The Mixed Grass Prairie, Wheatgrass-Needlegrass Type (figure 1), exists on semi arid cool soils between the Mesic Mixed Grass Prairie on the east and the Short Grass Prairie on the west and extends from mid Saskatchewan through western North Dakota and eastern Montana to north central and northwestern South Dakota. The physiography of the region consists of the eastern portions of the Glaciated and Unglaciated sections of the Missouri Plateau Section, including the Alberta Plain, of the Great Plains Province. The climate is semi arid with evapotranspiration greater than precipitation. The soil moisture regime is Ustic and the soil temperature regime is Frigid. The soils are primarily Typic Borolls. The major grasses of the Wheatgrass-Needlegrass Type of the Mixed Grass Prairie are western wheatgrass, needle and thread, blue grama, prairie Junegrass, and green needlegrass. Prominent forbs are white prairie aster, scarlet gaura, scarlet globemallow, purple prairie clover, dotted blazing star, purple locoweed, fringed sage, white sage, hairy golden aster, curlycup gumweed, Hood's spiny phlox, prairie smoke, green sage, and prairie chickweed. Major shrubs are silver sagebrush, buffaloberry, wild roses, western snowberry, broom snakeweed, and creeping juniper. This vegetation type grows in soils developed from glacial till north and east of the Missouri River and grows in soils developed from Tertiary sedimentary deposits south and west of the Missouri River. Soils in the unglaciated section are developing an argillic (clay) layer and accumulating soluble salts in a subhorizon at decreasing depths from east to west.

The Mixed Grass Prairie, Wheatgrass-Grama Type (figure 1), exists on semi arid warm clay soils south of the Wheatgrass-Needlegrass Type and is in southwestern South Dakota. The physiography of the region consists of the southeastern portion of the Unglaciated section of the Missouri Plateau Section of the Great Plains Province. The climate is semi arid with evapotranspiration greater than precipitation. The soil moisture regime is Ustic and the soil temperature regime is Mesic. The soils are primarily clay textured Typic Ustolls. The major grasses of the Wheatgrass-Grama Type of the Mixed Grass Prairie are western wheatgrass, blue grama, and buffalograss. This vegetation type is separated from the Wheatgrass-Needlegrass Type because the clay textured soils and warmer soil temperature regime result in near removal of needle and thread and in greatly increasing blue grama and buffalograss.

The Mixed Grass Prairie, Wheatgrass Type (figure 1), exists on semi arid warm dense clay soils south of the Wheatgrass-Needlegrass Type and is in northwestern South Dakota. The physiography of the region consists of the central portion of the Unglaciated section of the Missouri Plateau Section of the Great Plains Province. The climate is semi arid with evapotranspiration greater than precipitation. The soil moisture regime is Ustic and the soil temperature regime is Mesic. The soils are primarily dense clay textured Typic Ustolls. The major grasses of the Wheatgrass Type of the Mixed Grass Prairie are western wheatgrass, green needlegrass, and thickspike wheatgrass. This vegetation type is separated from the Wheatgrass-Needlegrass Type because the dense clay textured soils and warmer soil temperature regime result in removal of blue grama and near removal of needle and thread.

Short Grass Prairie

The Northern Short Grass Prairie, Grama-Needlegrass-Wheatgrass Type (figure 1), exists on the western side of the Northern Plains Grasslands and extends from southeastern Alberta and southwestern Saskatchewan through central Montana and southward into northeastern Wyoming. The physiography of the region consists of the western portions of the Glaciated and Unglaciated sections of the Missouri Plateau Section of the Great Plains Province. The climate is arid with evapotranspiration greater than precipitation. The soil moisture regime is Aridic and the soil temperature regime is Frigid in the north and Mesic in the south. The soils are primarily Aridic Borolls and Torriorthents in the north and Argids and Aridic Ustolls in the south. The major grasses of the Grama-Needlegrass-Wheatgrass Type of the Northern Short Grass Prairie are blue grama, needle and thread, small needlegrass, western wheatgrass, thickspike wheatgrass, green needlegrass, and buffalograss. Prominent forbs are fringed sage, green sage, milkvetches, Hood's spiny phlox, curlycup gumweed, and prairie chickweed. Major shrubs are big sagebrush, silver sagebrush, rabbitbrush, broom snakeweed, plains prickly pear, greesewood, shadescale, saltbush, and winterfat. Dr. Whitman (Barker and Whitman 1989) continued the separation of this vegetation type from the Wheatgrass-Needlegrass Type because of the notable increase in the shortgrass component and the relative decrease of western wheatgrass and needle and thread. Cool-season grass species increase towards the northern portions and warm-season grass species increase towards the southern portions. The needlegrasses increase in the north. Blue grama and buffalograss increase in the south. Because of the presence of mid cool-season grasses, the Northern Shortgrass Prairie has sometimes been combined with the Northern Mixed Grass Prairie. However, these two vegetation types are distinct and should remain separated. The Grama-Needlegrass-Wheatgrass Type has the appearance of a shortgrass prairie and has an arid soil moisture regime, less soil horizon development, shallower soil depth to the accumulating soluble salts and developing argillic (clay) layer, shallower rooting depth, lower soil water holding capacity, greater evapotranspiration potential, and generally more xeric than the Wheatgrass-Needlegrass Type.

The Northern Short Grass Prairie, Saltgrass Type, exists on salt affected soils distributed in local areas across the Northern Short Grass Prairie region. The major grasses of the Saltgrass Type of the Northern Short Grass Prairie are saltgrass, alkali cordgrass, basin wildrye, foxtail barley, little barley, and Nuttall's alkali grass. Few plant species can tolerate the harsh environmental conditions of salt-affected areas. The tolerant species have mechanisms to exclude uptake of salts, or physiologically separate and discharge the undesired salts.

The Southern Short Grass Prairie, Blue grama-Buffalograss Type (figure 1), exists in northwestern Nebraska and extends into east central Wyoming north of the North Platte River. The physiography of the region consists of a small western portion of the High Plains Section of the Great Plains Province. The climate is arid with evapotranspiration greater than precipitation. The soil moisture regime is Aridic and the soil temperature regime is Mesic. The soils are primarily Argids and Aridic Ustolls. The major grasses of the Blue grama-Buffalograss Type of the Southern Short Grass Prairie are blue grama and buffalograss. This vegetation type is separated from the Grama-Needlegrass-Wheatgrass Type because the arid soil moisture regime and mesic soil temperature regime severely reduce the mid cool-season grasses and greatly increase the short warm-season grasses. Only a small area of the Southern Short Grass Prairie extends into the Northern Plains.

Sandhills Prairie

The Sandhills Prairie, Bluestem-Sandreed-Grama-Needlegrass Type (figure 1), exists in the north central portion of Nebraska south of the Niobrara River and north of the Platte River. Other Sandhills Prairie areas exist scattered throughout the Northern Plains. Many areas are too small to map. A large area of Sandhills Prairie exists along the Sheyenne River in southeastern North Dakota and another large area exists near Swift Current, Saskatchewan. The physiography of the Nebraska Sandhills consists of the Sand Hills region of the High Plains Section of the Great Plains Province. The climate is semi arid with evapotranspiration greater than precipitation. The soil moisture regime is Ustic and the soil temperature regime is Mesic. The soils are primarily Ustipsamments. The major grasses of the Bluestem-Sandreed-Grama-Needlegrass Type of the Sandhills Prairie are big bluestem, little bluestem, sand bluestem, prairie sandreed, sideoats grama, needle and thread, and switchgrass. Prominent forbs are purple prairie clover, silky prairie clover, scurf peas, goldenrods, sunflowers, white camas, and wild lily. Major shrubs are leadplant, wild roses, western snowberry, willows, creeping juniper, common juniper, eastern red cedar, and yucca. This vegetation type is fundamentally the Tall Grass Prairie vegetation on sand soils. The tall grass species occupy the lower slopes and subirrigated soils while the mid and short grasses occupy the dryer upper slopes. A unique assemblage of grasses grow in blowout areas with active wind erosion and deposition and are blowout grass, sandhill muhly, sand dropseed, indian ricegrass, and Schweinitz cyperus.

Foothills Prairie

The Foothills Prairie, Plains Rough Fescue Type (figure 1), exists as a fringe along the montane forest of the Rocky Mountain foothills from Alberta to south central Montana and along the aspen groveland and aspen parkland bordering the boreal forest zone in Alberta and Saskatchewan and the type mingles with the Wheatgrass-Bluestem-Needlegrass Type extending across Saskatchewan and southwestern Manitoba and into northern North Dakota. The physiography of the region consists of the northern portion of the Glaciated section of the Missouri Plateau Section of the Great Plains Province and the northern portion of the Small Lakes Section of the Central Lowland Province. The major grasses of the Plains Rough Fescue Type of the Foothills Prairie are plains rough fescue, Parry's oatgrass, timber oatgrass, bluebunch wheatgrass, slender wheatgrass, western wheatgrass, thickspike wheatgrass, Nelson's needlegrass, and Richardson's needlegrass. Prominent forbs are lupines, tall larkspur, sticky-leaved geranium, and arrowleaf balsamroot. Major shrubs are shrubby cinquefoil and big sagebrush. This vegetation type consists of a high proportion of tussock-forming grass species that are now known to develop on other landforms than Rocky Mountain foothills.

Grassland with Woodland or Forest

The Pacific Bunchgrass Prairie, Bluebunch-Fescue Type (figure 1), exists in the south central portion of Montana. Numerous other areas too small to map exist within the Great Plains. The physiography of the region consists of the Unglaciated section of the Missouri Plateau Section of the Great Plains Province. The major grasses of the Bluebunch-Fescue Type of the Pacific Bunchgrass Prairie are bluebunch wheatgrass, Idaho fescue, western wheatgrass, sideoats grama, and little bluestem. Prominent forbs are white prairie aster, western yarrow, American vetch, scarlet gaura, and fringed sage. Major shrubs are western snowberry, silver sagebrush, rabbitbrush, broom snakeweed, and plains prickly pear. This vegetation type is commonly associated with big sagebrush and exists as open grasslands between savanna stands of ponderosa pine or Rocky Mountain juniper.

The Badlands and River Breaks, Woody Draw and Savanna Types (figure 1), exist in central Montana along the Missouri and Musselshell Rivers, in western North Dakota along the Little Missouri River, and in southwestern South Dakota along the White River. The physiography of the region consists of the Unglaciated section of the Missouri Plateau Section of the Great Plains Province. The major grasses of the Woody Draw and Savanna Types of the Badlands and River Breaks are western wheatgrass, needle and thread, blue grama, green needlegrass, and prairie Junegrass. The grassland communities of this vegetation type exist as open grasslands or understory grasslands associated with thin stands of trees growing in highly eroded badland areas, on steep east and north facing slopes, or in steep, sharply eroded breaks along streams and rivers. The woodlands and savannas consist primarily of ponderosa pine and Rocky Mountain juniper, and the hardwood draws consist of green ash, American elm, boxelder, and hawthorn. Major shrubs are wild roses, Juneberry, chokecherry, skunk bush, western snowberry, and shrubby cinequefoil.

The Pine Savanna, Pine-Juniper-Bluebunch Type (figure 1), exists on rough uplands in south central and southeastern Montana, north central Wyoming, western South Dakota, and southwestern North Dakota. The physiography of the region is the Unglaciated section of the Missouri Plateau Section of the Great Plains Province. The major grasses of the Pine-Juniper-Bluebunch Type of the Pine Savanna are bluebunch wheatgrass, western wheatgrass, thickspike wheatgrass, needle and thread, blue grama, green needlegrass, and little bluestem. The grassland communities of this vegetation type exist as open grasslands or understory grasslands associated with numerous disconnected savanna stands of ponderosa pine and Rocky Mountain juniper growing on eroded uplands with thin soils. Major shrubs are big sagebrush, bitterbrush, western snowberry, skunk bush, rabbitbrush, and common juniper.

The Black Hills Pine Forest, Pine-Spruce-Aspen Type (figure 1), exists in southwestern South Dakota and northeastern Wyoming. The physiography of the region consists of the Black Hills section of the Missouri Plateau Section of the Great Plains Province. The major grasses of the Pine-Spruce-Aspen Type of the Black Hills Pine Forest are western wheatgrass, bluebunch wheatgrass, needle and thread, green needlegrass, prairie Junegrass, and blue grama. The grassland communities of this vegetation type exist as open grasslands or understory grasslands associated with the open park stands of ponderosa pine in the higher hills and with the savanna stands of ponderosa pine in the lower hills. Grassland communities are not important in the deep cool canyons with dense, nearly closed stands of white spruce and paper birch, in the dense secondary growth of aspen and paper birch, or in the dense deciduous forest stands of green ash, bur oak, American elm, boxelder, and hackberry along streams. Important shrubs are beaked hazelnut, Juneberry, chokecherry, willows, big sagebrush, sand sagebrush, and mountain mahogany.

The Montane Forest, Pine-Fir-Spruce Type (figure 1), exists on the Sweetgrass Hills, and the Highwood, Bearpaw, Little Rocky, Moccasin, Judith, and Big Snowy mountains in Montana and the Cypress Hills in Saskatchewan. The physiography of the region consists of the laccolithic domed mountains in the Unglaciated section and the erosional upland remnant in the Glaciated section of the Missouri Plateau Section of the Great Plains Province. The major grasses of the Pine-Fir-Spruce Type of the Montane Forest are bluebunch wheatgrass, Idaho fescue, Nelson's needlegrass, spike fescue, prairie Junegrass, needle and thread, and spike oatgrass. The grassland communities of this vegetation type exist as open grasslands and understory grasslands associated with open stands of ponderosa pine and Douglas fir on the lower elevations of the domed mountains. Prominent forbs are arrowleaf balsamroot, lupine, sticky-leaved geranium, bluebells, and prairie smoke. Major shrubs are western snowberry, white spiraea, and bearberry. Grassland communities are not important at the higher elevations with closed forest stands of subalpine fir, Douglas fir, and Engelmann spruce. Grassland communities are associated with the open forest stands of lodgepole pine, white spruce, paper birch, and aspen on the Cypress Hills.

The Upland Woodlands, Aspen-Ash-Oak-Juniper Types (figure 1), exist as scattered areas with various types of trees, shrubs, and grasses in North Dakota, Manitoba, and Saskatchewan. The physiography of the region consists of upland positions of the Small Lakes Section of the Central Lowland Province and of upland positions of the Unglaciated section of the Missouri Plateau Section of the Great Plains Province. The major grasses of the Aspen-Ash-Oak-Juniper Types of the Upland Woodlands are roughleaf ricegrass, little ricegrass, and long-beaked sedge. Grass plants of these vegetation types are part of the understory community. Prominent forbs are northern bedstraw, wild strawberry, violets, anise root, and black snakeroot. Major shrubs are beaked hazelnut, western snowberry, Juneberry, chokecherry, red raspberry, bittersweet, gooseberry, wild plum, and northern hawthorn. The aspen woodlands contain trembling aspen, balsam poplar, paper birch, green ash, and sometimes bur oak. The ash woodlands contain green ash, American elm, boxelder, and occasionally hackberry. The oak woodlands contain bur oak, green ash, American elm, boxelder, aspen, and occasionally ironwood. The juniper woodlands contain Rocky Mountain juniper.

The Riparian Woodlands, Cottonwood-Ash-Elm Type (figure 1), exists along the floodplains of the larger rivers and streams and as small groves along minor drainage ways located throughout the Northern Plains. The major grasses of the Cottonwood-Ash-Elm Type of the Riparian Woodlands are Canada wildrye, slender wheatgrass, Virginia wildrye, prairie sandreed, needle and thread, green needlegrass, marsh muhly, reed canarygrass, prairie cordgrass, bottlebrush grass, and mountain ricegrass. The grassland communities of this vegetation type exist as understory grasslands associated with open woodlands and sometimes fairly dense forest stands of cottonwood, green ash, boxelder, American elm, hackberry, peach-leaved willow, and occasionally bur oak. Prominent forbs are false solomon's seal, dogbane, wild licorice, fringed loosestrife, and meadow rue. Major shrubs are western snowberry, wild roses, skunk bush, golden currant, gooseberry, dogwood, poison ivy, bittersweet, wild grape, thicket creeper, and western clematis.

The environmental and biological factors that affect development of plant communities and vegetation types are the same factors that affect soil development. Soil moisture regimes affect distribution of plant species affiliations. The species affiliations that are the major vegetation types in the Northern Plains; Tall Grass Prairie, Mesic Mixed Grass Prairie, Mixed Grass Prairie, and Short Grass Prairie; coincide with the four soil moisture regimes; Perudic, Udic, Ustic, and Aridic; respectively. The four soil moisture regimes are further separated into two soil temperature regimes; Frigid in the northern portions and Mesic in the southern portions. Soil temperature regimes affect composition and distribution of cool-season and warm-season grasses within the vegetation types. In the northern Frigid temperature regime, warm-season grass species decrease and cool-season grass species increase. In the southern Mesic temperature regime, cool-season grass species decrease and warm-season grass species increase.

Changes in elevation, slope, and aspect resulting from the various physiographic landforms in the Northern Plains affect plant species topographic distribution and plant community productivity by causing differential distribution and retention of soil water. Lower slopes have greater soil water than upper slopes. East and north facing slopes retain more soil water longer than south and west facing slopes. Lowland landscape slopes have soil water in amounts greater than precipitation levels because of water runin from upper slopes. Upland landscape slopes have soil water in amounts similar to precipitation levels because water runin and water runoff occur in low quantities and are about the same. Xeric landscape slopes have soil water in amounts less than precipitation levels because of restricted water infiltration, low water holding capacity, high evapotranspiration demand, and/or high water runoff.

Some slope positions have sufficiently low evapotranspiration demand and/or receive sufficient quantities of water runin for woodland and forest plant communities to develop. Woodlands and forests also develop along rivers and streams and at higher elevation positions that receive greater quantities of precipitation.

Enhancement of the Land Natural Resources

Generating greater new wealth with livestock agriculture requires enhancement of the land natural resources. These essential changes are doable and not the herculean task that they first appear to be. A few small catalyzing changes correctly timed can have remarkable effects.

The forces that change hills into valleys, rocks into clay, and forests into grasslands work slowly over thousands and millions of years. The physiographic landform characteristics have changed little during the past 10,000 years. The current climate with wet and dry periods, and the current soil moisture and soil temperature regimes have been operational for about 5,000 years. The native plant species completed development of their physiological processes and defoliation resistance mechanisms in conjunction with early herbivore dinosaur evolution millions of years ago.

By contrast, the soils, plant communities, and vegetation types in the Northern Plains are relatively young and their development is still ongoing. These developmental processes can be manipulated through implementation of biologically effective management that benefits all living and nonliving ecosystem components by meeting the biological requirements of the plants and soil organisms which causes improvements in the biogeochemical processes, ecosystem health, soil quality, plant community composition, and vegetation type affiliations. These important improvements enhance the quality and productivity of the land natural resources and result in generation of greater new wealth.

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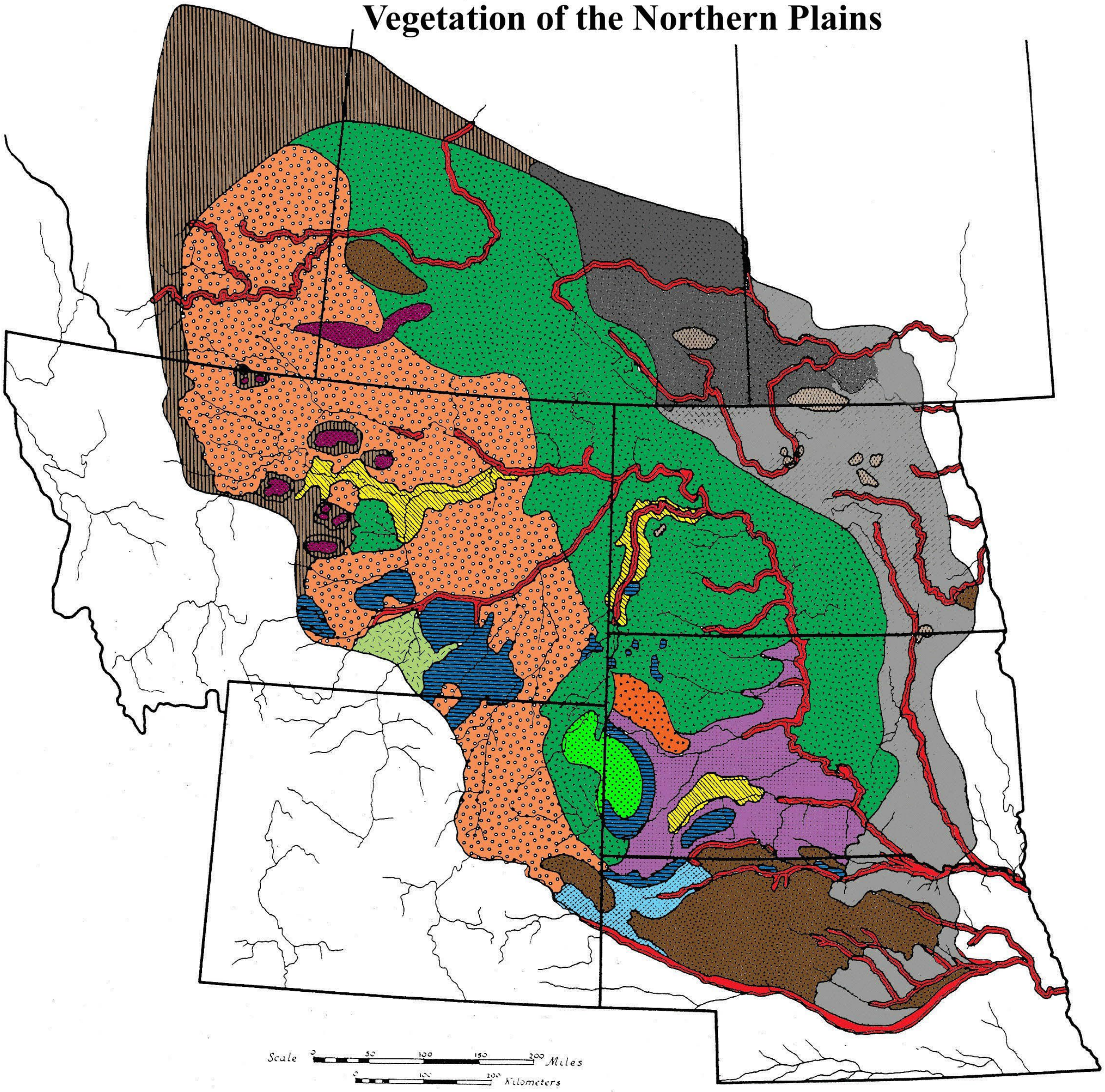
Vegetation of the Northern Plains



map from Barker and Whitman 1989

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Primary Stages of Progress in Grassland Management

The Northern Plains south of Canada became part of the United States when the Territory of Louisiana was acquired from the French Emperor Napoleon Bonaparte for $15 million in 1803. The Northern Plains remained a wide open prairie grazed by free roaming bison until the late 1800's. The Northern Pacific Railroad was granted 39 million acres of land in a checkerboard pattern from Duluth, MN to Puget Sound, WA. The railroad was constructed across the Northern Plains during 1871 to 1881. Buffalo hunters greatly reduced the bison population and shipped 1.5 million bison hides from the region between 1880 and 1884. Several large herds of light weight 2 to 4 year old steers and dry cows were trailed north from Texas during 1882 and 1883 to be fattened on Northern Plains open range grasses. In 1884, the number of cattle was estimated to be between 30,000 and 40,000 head at a light stocking rate of 80 to 100 acres per animal for a year of grazing and in 1886 the district was declared to be fully stocked. Unfortunately, the winter conditions of 1886-1887 were very severe with numerous blizzards and long spells of bitter sub-zero temperatures. By spring, 50% to 75% of the cattle had been lost. This ended the five year experiment of grazing 12 months on open range. The small number of remaining outfits maintained relatively small herds. Beef breeds of Angus, Herefords, and Shorthorns were brought in to replace the Texas cattle. Hay was cut with horse drawn mowers with 5 foot cutting bar. Some operations cut hay until October or snowfall, but the quality of the late cut hay was below the livestock nutrient requirements and alfalfa was brought in to improve the winter hay quality (Manske 1994).

The human population of the Northern Plains greatly increased during 1898 to 1915 with the peak period between 1900 to 1910 because of the influx of people wanting to claim 160 acres of homestead land. The lawmakers caused several long lasting problems because they failed to address the requirements of the semi arid and arid natural resources of the Northern Plains and they failed to provide the needed technology for proper management of these lands. Some scientific assistance to the homesteaders was provided by land grant universities during the 1910's and 1920's (Hanson and Whitman 1938).

Grazing Based on Seedlings

During the early years of homesteading the Northern Plains, there were no scientists trained in management of perennial grasslands. Agronomically trained scientists were tasked with the initial research. The published hypothesis on how to improve degraded grasslands was to reseed the land with mechanical methods (Jardine 1916). Following this agronomic hypothesis, Sampson (1913, 1914, 1923) developed the deferred-rotation grazing system that deferred grazing on one of the three pastures each year until late season after grass seeds had been produced and then cattle were intended to scatter and trample the seeds into the soil in order to promote seedling establishment. Working at the Mandan ARS station, ND, J.T. Sarvis developed grazing guidelines that required 15% to 25% of the annual forage production to remain at the end of the grazing season. During 1918 to 1940, Sarvis (1923, 1941) evaluated Sampson's deferred-rotation treatment for use in the Northern Plains. The research animals were two year old grade steers of standard beef breeds with the mean initial weight of 750 pounds. The steers on the deferred-rotation treatment gained 19% less weight than the steers on the seasonlong treatment. After 23 years, Sarvis (1941) saw no significant benefit from reseeded grass. Scientists working during the 1910's and 1920's with perennial grasses, knew that some grasses produced vegetative tillers, but that was dismissed as unimportant. Many years later, vegetative tiller growth was recognized as the dominant form of reproduction in perennial grasses (Belsky 1992, Chapman and Peat 1992, Briske and Richards 1995, Chapman 1996, Manske 1996, 1999) not sexual reproduction and the development of seedlings. Any grazing practice designed to enhance grass seed production and seedling development, like the deferred-rotation practice, are obsolete.

Increasing Forage Quality with Alfalfa

In the early 1900's, alfalfa was a potential promising forage plant. Professors Charles J. Brand and Lawrence R. Waldron established exhaustive comparative alfalfa variety tests at the North Dakota Agricultural Experiment Station at Fargo and Dickinson in 1902. Among their tests were traits for yield, winter hardiness, and alfalfa bacteria (rhizobium). One of their conclusions was that Grimm alfalfa was a natural cross between the common purple blossom alfalfa, Medicago sativa, and a “wild” yellow flowering species, Medicago falcata (Edwards and Russel 1938).

N.E. Hansen, the famous alfalfa horticulturist of South Dakota Experimental Station, made several trips to Eurasia to locate suitable seed of Medicago falcata, the pasture type alfalfa that had fibrous roots and short rhizomes with meristematic tissue that could produce vegetative buds. Hansen promoted the use of Medicago falcata alfalfa to increase production of Northern Plains grassland and mailed packets of seeds to homesteaders to plant into plowed land or broadcast into intact grasslands (Rumbaugh c. 1979). A few locations with alfalfa plants from Hansen's seed packets are still growing on Northern Plains grasslands. However, establishment of alfalfa plants by broadcast sod-seeding into native grasslands has phenomenally low success rates. Development of a capable interseeding machine and effective establishment techniques needed to be researched if interseeding alfalfa into grasslands was to be successful.

South Dakota Experiment Station scientist have developed several versions of interseeding machines and are still working on alfalfa variety selection. A few USDA plant material centers and Ag Canada are still working on development of pasture type alfalfa varieties. Dickinson Research Extension Center has tested several modifications of interseeding machines and interseeding techniques (Manske 2005).

Successful interseeding alfalfa into intact grassland ecosystems without great destruction to the grassland has several major problems. Alfalfa seeds require direct access to moist mineral soil and must have severely reduced competition from the existing grassland plant community. Several techniques have had some success but no technique has been consistently successful. Alfalfa plants interseeded into low mineral nitrogen grasslands are highly dependent on the symbiotic relationship with rhizobium bacteria that can fix mineral nitrogen from soil air. Seeding inoculated alfalfa seed into intact grasslands is very different from seeding into old cropland. Degraded grasslands have much greater biomass of indigenous soil microbes than cropland. These soil microbes are capable of consuming all of the inoculated rhizobium bacteria before the alfalfa seedlings have enough root for the rhizobium to nodulate. Thus, if the seedling survives, it receives no nitrogen from rhizobium, and it than is in direct competition with the grassland plants for the low quantity of available mineral nitrogen. The low percentage of alfalfa plants that do become established become major competition to the grass plants for sunlight, soil mineral nitrogen, and soil water. Native grasses need near full sunlight and any shading greatly reduces grass production. Healthy grasses are excellent competition for soil mineral nitrogen and water, however, weak grasses are not. Alfalfa plants have a high water use and alfalfa roots can extend in a 5 foot radius from an alfalfa crown and can deplete soil water to a 4 foot depth an average of 35% below ambient soil water in soil that has no alfalfa roots. During normal rainfall growing seasons, grass plants are in drought conditions when alfalfa roots are present. The native grasses within 5 feet of an established alfalfa crown decrease rapidly and Kentucky bluegrass is the major replacement grass. When the alfalfa seedlings fail to become established, the large mineral soil seed bed is unoccupied and smooth bromegrass is usually the major replacement grass (Manske 2005).

Development of Stocking Rate

The naive homesteaders, had no technological assistance from the government on how to properly manage Northern Plains grasslands; they implemented eastern grazing practices with stocking rates at greater than 60% heavier than the biological carrying capacity for grasslands west of the 20 inch rainfall line. As a result, the grassland resources deteriorated and herbage biomass production decreased with disproportional reduction of mid cool season grass species, and leaving a predominance of short warm season grass species (Whitman et al. 1943). Branson (1953) determined that grass species with long shoots that elevated the apical meristem above grazing height decreased at greater rates than grass species with short shoots that kept the apical meristem below grazing height in pastures that are repeatedly grazed with heavy stocking rates. Crider (1955) determined biologically that stocking rates should only remove about 50% of the herbage biomass because grass tillers that had more than 50% of the aboveground leaf and stem material removed would develop reduced root growth, root respiration, and root nutrient absorption causing grass plant deterioration.

Crider's (1955) monumental research to determine the biological threshold level of herbage weight removal from grass plants was desperately needed to set proper stocking rates. Crider's work was some of the first grassland research to actually study the belowground components in order to determine how to manage the aboveground components. He also showed that biological, physiological, and ecological sciences could be effectively applied to develop proper grassland management practices. Coyne et al. (1995) has determined that grass plants produce double the quantity of aboveground leaf and stem biomass than is needed for photosynthesis and normal growth and development. This is the portion that is expendable from Crider's (1955) research.

Scientists have also determined that Crider's 50% plant material removal does not work at all phenological growth stages of grass. Briske and Richards (1995) determined that stored root carbohydrates were not remobilized to support replacement shoot growth following partial defoliation by grazing livestock. The carbohydrates needed for replacement shoot growth must come from currently fixed carbon during photosynthesis in remaining and rejuvenated leaf area from existing shoot material. A problem develops when 50% of the grass herbage is removed during lead tiller vegetative growth stages between the 3.5 new leaf stage and the flower (anthesis) stage, the remaining 50% leaf area cannot supply adequate quantities of currently fixed carbon causing grass tiller density to be reduced 13% per year. However, when only 25% of the grass herbage is removed during lead tiller vegetative growth stages, the quantity of young leaf material removed also removes sufficient quantities of the growth-inhibiting hormone, auxin, which then permitted the synthesis or utilization of the growth hormone, cytokinin, to activate the asexual processes of vegetative tiller production in several axillary buds. The remaining 75% leaf weight had sufficient leaf area to fix carbon at adequate quantities for growth and development of these vegetative tillers at a level that beneficially increased tiller density 25% per year (Manske 2014a, b).

Development of Grazing Start Date

Proper grazing start date is another critical factor in management of grasslands. The first attempt to set a scientific grazing start date for the native grasslands of the Northern Plains was determined by concensus of many highly experienced range scientists that selected 15 June as a result of interpretation of data collected on a four year grazing study conducted at Swift Current, SK (Campbell 1952) and a four year clipping study conducted at Mandan, ND (Rogler et al. 1962) that determined the percentage of herbage biomass reduction at 6 different defoliation start dates compared to the potential peak herbage biomass on an undisturbed control site. The scientifically determined grazing start date for Northern Plains grasslands was 15 June until the late 1990's, when a physiological growth stage of grasses was found that had negative effects from defoliation before and positive effects from partial defoliation after. Scientists at the Mandan ARS station were conducting several years of very detailed grass growth stage studies to better understand grass development. They determined that second year young lead tillers cease production of leaf primordia in the apical meristem at the third new leaf stage and are actively producing flower primordia by the three and a half new leaf stage (Frank 1996, Frank et al. 1997). Thus, before the third new leaf stage, grasses are negatively affected by partial grazing defoliation and after the three and a half new leaf stage, grasses are positively affected by partial defoliation that removes 25% to 33% of the lead tiller aboveground herbage weight (Manske 1999).

During 1983 to 1989, Manske conducted a grass phenological development study that measured leaf height and percent leaf senescence of every leaf of 10 ungrazed vegetative and reproductive tillers, and also recorded flower stalk growth stages biweekly from June through August on sandy, shallow, silty, and clayey ecological sites with both grazed and ungrazed treatments from seasonlong and twice-over grazing strategies and on the long-term ungrazed control. This study was able to determine that the major native cool season grasses reached the three and a half new leaf stage just before, near, or on 1 June, prairie sandreed was the first warm season grass to reach the three and a half new leaf stage soon after 1 June, and the other native warm season grasses reached the three and a half new leaf stage by mid June (Manske 2020). The grazing start date on Northern Plains native grasslands can be 1 June each year.

Increasing Soil Mineral Nitrogen

Scientists had known from very early in the 1900's that Northern Plains grasslands managed by standard traditional practices were deficient in available mineral nitrogen. The uninformed homesteaders that had not been provided the needed technology to properly manage Northern Plains grasslands implemented eastern practices that caused millions of grassland acres to deteriorate. After World War II, low cost ammonium nitrate fertilizer became available. Application of nitrogen fertilizer to native grasslands was extensively studied at the ARS Stations at Mandan, ND and Sidney, MT and at the NDSU Dickinson Research Extension Center, ND. The first couple of years of research with the application of various rates of ammonium nitrate to deteriorated native grasslands showed an increase of the long shooted grass species and some decrease of the short shooted grass species, which seemed to be exactly what these grasslands needed. It did not take too long to show that the decrease in the short warm season grasses resulted in an increase in bare spaces which caused an increase in soil temperature and an increase in water evaporation. In addition, the nitrogen fertilizer caused a serious biological complication with the soil microbes causing a great reduction in their biomass and a loss of the ecosystem biogeochemical processes resulting in a great reduction in ecosystem functionality and a loss of native grass species. Ten years of nitrogen fertilizer application caused a complete change from a native grassland to replacement grassland with a combination of smooth bromegrass, Kentucky bluegrass, and crested wheatgrass (Manske 2014c).

Northern Plains grasslands do not need additional nitrogen fertilizer applied to the soils. Intact grasslands contain a wide range of 3 to 8 tons/ac, with most land at 5 to 6 tons/ac of organic nitrogen that accumulated a few pounds per year over a period of 5,000 years (Brady 1974). Organic nitrogen is not available for plant growth. Organic nitrogen must be transformed by soil microbes to mineral nitrogen. Which means that Northern Plains grasslands were not short of nitrogen but were short of soil microbe biomass to transform the organic nitrogen. Unfortunately, the soil microorganism information was unknown until the 1980's. Coleman et al. 1983, Ingham et al. 1985, and Clarholm 1985, described the rhizosphere organisms and the basic science of how they interacted and the biogeochemical processes they performed. With much regret, these basic scientists did not study the applied science aspects of how to increase their biomass and ways to increase their transforming processes to increase the soil available mineral nitrogen quantity. Wight and Black (1972, 1979) had determined the threshold quantity of available mineral nitrogen needed to be at a minimum of 100 lbs/ac (112 kg/ha) in order for the precipitation (water) use efficiency mechanisms in grasses to function at biological potential. Manske (2010a, b) determined activation of the compensatory physiological processes and the asexual processes of vegetative tiller production in grass lead tillers also required available mineral nitrogen to be at 100 lbs/ac (112 kg/ha) or greater. Manske (1996, 1999, 2018a) described the applied science aspects and the biologically effective grazing management practices needed to elevate the soil rhizosphere microorganism biomass enough for the microbes to transform a greater quantity of available mineral nitrogen. The rhizosphere biomass has to be a little greater than 214 kg/m^3 in order to transform the threshold quantity of 112 kg/ha (100 lbs/ac) of available mineral nitrogen (Manske 2012).

Development of Complementary Grazing

Extension of the grazing season by 2 months (56 to 64 days) by the addition of spring and fall complementary pastures of introduced domesticated grasses to a summer grazed native grassland pasture should improve livestock weight performance. Grazing forage grasses is more efficient and effective when the phenological growth stages, the herbage production curves, and the nutrient quality curves of the forage sources match the biological and physiological requirements of the grazing livestock. This action of coordination between the primary producers and the primary consumers is called “seasonality”. All of the perennial forage grasses growing in the Northern Plains region have growth characteristics that can be categorized into three seasonality units. The spring unit can be 28 or 32 days long during early to late May includes the introduced domesticated cool season grasses, like crested wheatgrass and smooth bromegrass. The summer unit can be 135 to 137 days long during early June to mid October includes the cool season and warm season native grasses; no introduced domesticated grasses are qualified for the summer unit. The fall unit can be 28 to 32 days long during mid October to mid November includes all of the wildryes, like Altai and Russian wildrye. The fall unit can also include spring seeded winter cereal grasses, like winter rye. The total combination grazing period can be 191 to 201 days long during early May to mid November. There are no perennial grasses that can grow in the Northern Plains that qualify biologically for grazing during mid November to late April. This nongrazing period can be 164 to 174 days long (Manske 2018e).

Scientists from the Swift Current Research Branch in southwestern Saskatchewan and the NDSU Dickinson Research Extension Center in western North Dakota have worked extensively on the development of complementary grazing systems based on the seasonality concept for the Northern Plains. Initially, both research centers used a simple three pasture system with crested wheatgrass, native grassland, and Russian wildrye, and both research centers have also worked with Altai wildrye as the fall pasture.

Belowground Mechanisms and Biogeochemical Processes

Grassland ecosystems are complex and have biotic and abiotic components above and below ground. Proper management of grasslands requires consideration of all of these components. Fortunately, there was a period during the late 1970's through the 1990's when numerous basic scientists were inspired to research the belowground portions of grasslands and discovered the basic sciences of the complex processes and mechanisms along with the ecosystem biogeochemical processes that enable grassland ecosystems to function at biological potential levels. A few of the more profound studies were: McNaughton (1979, 1983) explained grass compensatory growth following partial grazing defoliation; Coleman et al. (1983) explained the symbiotic rhizosphere microorganisms; Richards et al. (1985, 1988) explained regrowth and vegetative tillering following grazing defoliation; and Briske and Richards (1994, 1995) explained grass plant compensatory physiological processes that replaced removed leaf and stem material after partial grazing defoliation. As monumentally important as these collective basic science studies are, these basic scientist did not conduct any applied science research to show how to make these necessary processes and mechanisms to actually work in grassland ecosystems. That needed applied science research was conducted at the NDSU Dickinson Research Extension Center during 1983 through 2018 and reported in Manske (2018 a, b, c, d, e, 2019).

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Problems from Nonseasonality Grazing

Problems of Grazing Too Early

Preseasonality grazing of native grasslands during April and May prior to the new second year lead tillers reaching the three and a half new leaf stage are the previous years vegetative tillers that have survived overwinter on carbohydrate reserves that were stored by the tiller during the winter hardening process that occurs between mid August and hard frost. These carryover tillers are low in carbohydrate reserves that are inadequate to support root growth and new leaf growth. Partial defoliation by grazing is antagonistic to further tiller growth and to rhizosphere microbe activity. Spring growth depends on remaining quantities of carbohydrate reserves and on photosynthetic product from portions of previous years leaves that did not have cell wall rupture and regreened with chlorophyll (Heady 1975, Coyne et al. 1995). Additional leaf and root growth requires that the young lead tillers maintain adequate leaf area with a combination of carryover leaves and new leaves. At the time the new lead tiller has produced the third new leaf, the apical meristem would have produced 6 to 8 leaf buds and it stops producing leaf bud primordia and begins producing flower bud primordia by the three and a half new leaf stage. At this stage, the young lead tillers are nearly depleted of carbohydrates and the chlorophyll in the carryover leaves is senescing, and the tillers are capable of surviving removal of 25% of the new leaf growth but not removal of 50% of the new leaf area (Manske 2010a, b, 2014a, b).

Defoliation of new young lead tillers prior to the three and a half new leaf stage terminates any beneficial activation of the four internal grass growth mechanisms, stops vegetative tillering mechanisms (Olson and Richards 1988, Vogel and Bjugstad 1968) and prevents development of surplus short chain carbon energy from being exuded into the rhizosphere to stimulate microorganism activity and the ecosystem biogeochemical processes. The remaining new leaf area is unable to photosynthetically support additional active leaf growth (Coyne et al. 1995). That tiller does not die but attempts to slowly produce leaf and root tissue at rates far below its potential rate and quantity of herbage production causing a great decrease in peak herbage biomass later in the growing season (Manske 2000). Grazing that starts in early May on native grasslands results in a reduction of more than 75% of the potential herbage biomass. When grazing starts in mid May, from 45% to 60% of the potential herbage biomass is not produced that growing season (Campbell 1952, Rogler et al. 1962, Manske 2000).

Problems of Standard Traditional Practices

Traditional grazing practices are primarily designed to only provide forage for livestock and not ecosystem functionality, and are antagonistic to rhizosphere organism activity and the internal grass growth mechanisms. Grass lead tillers produce surplus carbohydrates during vegetative growth stages that could supply the needed short chain carbon energy to the rhizosphere microbes. However, traditional grazing practices inhibit the surplus carbon energy from being exudated through grass roots into the rhizosphere causing the microbe biomass to remain low preventing the transformation of organic nitrogen into mineral nitrogen at threshold quantities at 100 lbs/ac or greater which then prevents the internal grass growth mechanisms from being activated resulting in decreases in grass density and herbage biomass production. After a few years these losses in productivity are substantial. The deferred-rotation treatment caused a 70.6% decreases in available mineral nitrogen after 35 years. The 6 month seasonlong treatment caused a 41.9% decrease in mineral nitrogen and a 51.2% decrease in rhizosphere volume after 20 years. The 4.5 month seasonlong treatment caused a 27.7% decrease in mineral nitrogen and a 33.7% decrease in rhizosphere volume after 20 years (Manske 2011).

Problems of Deferred Grazing Start Date

Deferring the starting date of grazing on native grasslands until after grassland tillers have developed seeds prevents the activation of the internal grass growth mechanisms and stimulation of rhizosphere organism activity and the ecosystem biogeochemical processes. The reduced quantity of herbage biomass drops below the nutritional crude protein requirements of lactating beef cows during late July (Whitman et al. 1951, Manske 1999b) because of lead tiller leaf senescence and the translocation of cell constituents from leaf structures (Langer 1972, Beard 1973, Leopold and Kriedemann 1975). The early agronomic intended purpose of a deferred grazing start date was to promote grass seedling establishment, however, grass seedling recruitment is not the major type of grass plant increase; vegetative tiller growth is the dominant form of reproduction in perennial grasses (Manske 1999a).

Problems of Repeated Heavy Grazing

Severe defoliation that removes greater than 50% of the leaf material and repeated defoliation with rapid frequency results in insufficient leaf area retained on the tiller for even partial foliage recovery using current photosynthetic assimilates. Tillers with more than 50% of the aboveground leaf material removed reduce root growth, root respiration, and root nutrient absorption (Crider 1955). Root mortality and decomposition begin within 2 days of severe leaf defoliation (Oswalt et al. 1959). Severely defoliated tillers only have very small quantities of stored carbohydrates upon which they must depend for partial replacement of leaf and root growth (Briske and Richards 1995). There is a high biological cost to the tiller when the photosynthetic system needs to be replaced from low quantities of stored carbohydrates. This implied reduction in efficiency results in reduced total root growth, decreased tiller development, and very low growth rates causing decreased tiller numbers, reduced total basal area, and reduced quantities of herbage biomass produced (Chapin and Slack 1979, Olson and Richards 1988, Coyne et al. 1955). Continuation of severe defoliation inhibits herbage production further as a result of additional restrictions caused by low levels of stored carbohydrates (Coyne et al. 1995).

Problems of Grazing Late Season

Post seasonality grazing of native grasslands after mid October does not harm the senescent lead tillers that produced seed during the growing season. Unquestionably, all the other tillers; the vegetative tillers, the secondary tillers, the fall initiated tillers, and even the next spring initiated tillers are severely negatively affected by post seasonality grazing after mid October. Vegetative reproduction of grass tillers is the dominant form of grass recruitment. Very few grass seedlings exist in grasslands. All grass vegetative tillers live for two growing seasons. The secondary vegetative tillers will be the future young lead tillers. They store carbohydrates for winter survival only during the winter hardening period of mid August to hard frost. Winter dormancy in perennial grasses is not total inactivity, but reduced activity (Leopold and Kriedemann 1975). The crown, portions of the root system, and some leaf tissue remain active and maintain physiological processes throughout the winter by using stored carbohydrates. Cool-season grasses continue leaf growth at slow rates during the winter. Some tillers with low carbohydrate reserves do not survive until spring. The rate at which plants respire, or use, stored carbohydrates during the winter is affected by the amount of insulation standing plant material and snow cover provide from the cold winter air temperatures. The greater the amount of insulation, the more slowly the plant draws on its carbohydrate reserves. The lower the quantity of insulation, the greater the rate of respiration and the greater the chance of depletion of the carbohydrate reserves before spring, causing tiller death called "winter kill". These carryover tillers that survive are always low in carbohydrates the next spring. Grass new leaf growth depends mostly on the carryover leaves that regreen in the spring and provide the crucial photosynthetic product for most of the new leaf growth in the spring (Briske and Richards 1995). If those carryover leaves are grazed during the previous fall, that grassland will lose those new leaves that the missing carryover leaves would have produced (Coyne et al. 1995) which greatly decreases the quantity of forage that would have been produced the following growing season (Goetz 1963, Manske 2003).

Problems of Grazing Below Stocking Rate

Grass plants produce double the leaf and stem biomass needed for photosynthesis and normal growth and development (Coyne et al. 1995). This portion of the grass weight is expendable by the plant (Crider 1955). The surplus standing leaf material accumulates rapidly and changes from an asset to a detriment if graminivores do not remove it by grazing. When a grassland is managed by the biologically effective twice-over rotation strategy, the surplus carbohydrates produced by vegetative lead tillers are exudated through the roots into the rhizosphere and increase the biomass of the soil microbes. The larger biomass of microbes can then transform organic nitrogen into mineral nitrogen at quantities greater than 100 lbs/ac. When mineral nitrogen is available at 100 lbs/ac or greater, the internal grass growth mechanisms of compensatory physiological growth, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency mechanisms can be fully activated and are capable of increasing herbage biomass production. As the herbage biomass increases, the stocking rate should be increased at 10% per year until the stocking rate is 140% of the seasonlong rate, which, has been the biological potential of the twice-over system in the Northern Plains. The increase in stocking rate must match the increase in grass herbage biomass. If the stocking rate remains at 80%-100% of the seasonlong rates and the herbage biomass increases to 140%, the surplus accumulating standing leaf biomass shade the lower leaves, increasing the rate of leaf senescence and reducing the rate of photosysnthesis, causing a decrease in the supply of carbohydrates that results in a reduction in growth of leaves and roots (Langer 1972, Briske and Richards 1995). Lack of grazing the surplus leaves reduces grass tiller densities by decreasing tiller development and increasing tiller mortality through shading (Manske 1999a). After a few years, the shading increases, the composition of native grass species reduces, and the composition of shade-tolerant replacement species, like Kentucky bluegrass increases. The only way to prevent this unwanted grass species change from happening is by increasing the stocking rate as the rate of herbage biomass increases.

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Applying the Science to Grasslands

Triad Components

Grasslands are comprised of three indispensable components; the Grass Vegetation, the Soil Rhizosphere Organisms, and the Grazing Graminivores. A grassland cannot function properly at biological potential levels without all three indispensable components performing at their biological potentials. To put this triad inter relationships into perspective we can prorate each components weight to an acre of grassland. Each 1200 lb cow with a calf stocked at 2.26 ac/AUM and 10.22 ac/AU for 4.5 months of summer grazing has a mean area weight of **117.4 lbs/ac**. The herbage biomass with a peak standing weight at 2242 lbs/ac has a roughly estimated annual net primary productivity (NPP) at between 4600 to 8381 lbs/ac with a mean of **6490.5 lbs/ac**. The rhizosphere organisms have a standard reference weight at 406.44 kg/m^3 which converts to **1813.5 tons/ac** that is 39 inches deep. The rhizosphere microbes transform soil organic matter (SOM) into mineral forms of essential elements, the grass plants use the mineral elements to synthesize organic compounds, and livestock use these organic compounds to increase growth of body weight. Livestock are heterotrophic animals and cannot produce their own food from mineral elements. Livestock body weight comes from the organic compounds synthesized by grass plants from the mineral essential elements that had been transformed from soil organic matter by the rhizosphere microbes. The grass plants and rhizosphere microbes that live on the grassland natural resources are the true source of wealth captured by livestock agriculture. Grassland management strategies that meet the biological and physiological requirements of the grass plants and rhizosphere microbes will also meet the nutrient requirements of the livestock and will capture greater wealth per acre than traditional practices that manage grasslands to provide low cash costs of forage for livestock.

Solution to Inherent Biological Problems

Grass lead tillers drop below the levels of crude protein requirements of lactating cows during late July (Whitman et al. 1951). Grasslands managed with traditional practices provide forage that is low in crude protein from early August to the end of the grazing season. This causes cow milk production to greatly decrease and calf weight gains to decrease to rates below their genetic potentials. The common remedy for this annual problem is to provide costly lick tubs for the cows and creep feed for the calves. There is a biological solution built into grasslands. Perennial grasses reproduce vegetatively by activated growth of axillary buds. The axillary buds are inhibited from growing by the hormone, auxin, that is produced in the apical meristem and young developing leaves of second year lead tillers (Briske and Richards 1995). Partial defoliation by grazing graminivores that removes 25%-33% of the young leaf material from grass lead tillers at phenological growth between the three and a half new leaf stage and the flower stage during 1 June to 15 July also removes enough auxin that permits the growth hormone, cytokinin, to stimulate vegetative growth of secondary tillers from the meristematic tissue in axillary buds which will provide adequate crude protein for lactating cows to maintain milk production and calf rate of weight gain at near genetic potential from late July until mid October. However, the growth and development of the stimulated secondary tillers requires mineral nitrogen to be available at 100 lbs/ac or greater. Intact grasslands contain 5 to 6 tons of organic nitrogen per acre which must be transformed by soil microbes into mineral nitrogen. Traditional grazing management practices usually only have enough soil microbe biomass to transform 50 to 60 lbs/ac of mineral nitrogen.

Lead tillers at vegetative growth stages between the three and a half new leaf stage and the flower stage produce surplus carbohydrates that can be exudated through the roots into the rhizosphere and increase the microbe biomass with partial defoliation by grazing graminivores that removed 25%-33% of the lead tiller leaf material. The response from the rhizosphere microbes is not instantaneous. During the first two growing seasons, the rhizosphere change is no different than that on the nongrazed control. During the third year to sixth year the rhizosphere biomass increases. When the microbe biomass reaches a little more than 214 kg/m^3, the microbes will be able to mineralize around 112 kg/ha (100 lbs/ac) of mineral nitrogen. When 100 lbs/ac of mineral nitrogen is available, the internal grass growth mechanisms of compensatory physiological growth, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency mechanisms can be fully activated. The twice-over rotation system is the only management strategy known to be able to maintain a large biomass of rhizosphere microbes that can mineralize greater than 100 lbs/ac of mineral nitrogen and to activate the four internal grass growth mechanisms.

Implementation of a Biologically Effective Management Strategy

Spring Complementary Pasture

The spring complementary pasture is unfertilized crested wheatgrass with no alfalfa. The pasture is split into equal halves with each portion grazed during 2 alternating 7 or 8 day periods in a switchback plan stocked at 1.30 ac/AUM (stocking rates greater than 1.25 ac/AUM are too heavy) grazed for 28 or 32 days, respectively, from early to late May, plus one day. The calves need to be one month old on 1 May at the start of the grazing period; calves less than one month old cannot gain much more than 1.25 lbs/day. Crested wheatgrass alone has adequate crude protein during May for steers, heifers, and cow-calf pairs. Older studies used a mixture of 40% to 60% alfalfa that showed no clinical signs of bloat in any of the livestock, however, the livestock weight performance on the alfalfa mixture was reduced 17% compared to similar animals grazing crested wheatgrass without alfalfa (Manske 2018).

Management of the Twice-over System

The biologically effective twice-over rotation strategy was designed to coordinate partial defoliation events with grass phenological growth stages, to meet the nutrient requirements of the grazing graminivores, the biological requirements of the grass plants and the rhizosphere microorganisms, to enhance the ecosystem biogeochemical processes, and to activate the internal grass plant growth mechanisms in order for grassland ecosystems to function at the greatest achievable levels.

The twice-over rotation grazing management strategy uses three to six native grassland pastures. Each pasture is grazed for two periods per growing season. The number of grazing periods is determined by the number of sets of tillers: one set of lead tillers and one set of vegetative secondary tillers per growing season. The first grazing period is 45 days long, ideally, from 1 June to 15 July, with each pasture grazed for 7 to 17 days (never less or more). The number of days of the first grazing period on each pasture is the same percentage of 45 days as the percentage of the total season's grazeable forage contributed by each pasture to the complete system. The forage is measured as animal unit months (AUM's). The average grazing season month is 30.5 days long (Manske 2012). The number of days grazed are not counted by calendar dates but by the number of 24-hr periods grazed from the date and time the livestock are turned out to pasture. The second grazing period is 90 days long, ideally from 15 July to 14 October, each pasture is grazed for twice the number of days as in the first period. The length of the total grazing period is best at 135 days; 45 days during the first period plus 90 days during the second period.

There is some flexibility in the grazing period dates. The starting date has a variance of plus or minus 3 days with a range of start dates from 29 May to 4 June. This gives an extreme early option to start on 29 May with the first period to 12 July and with the second period to 11 October. The extreme late alternative option can start on 4 June with the first period to 18 July and with the second period to 17 October. There is also the option to add a total of 2 days to the total length of the grazing period. These 2 days can be used when a scheduled rotation date occurs on an inconvenient date by adding one day to each of two rotation dates. The limit of additional days is two per year resulting in a total length of 137 days. If inconvenient rotation dates occur during 3 or more times, an equal number of days greater than two must be subtracted from the grazing season, so total number of days grazed per year does not exceed 137 days. If the start date is later than 4 June, the scheduled rotation dates must remain as if the start date were on 4 June, in order to maintain the coordinated match of the partial defoliation events with the grass phenological growth stages. The total number of days grazed will be 135 days minus the number of days from 4 June to the actual start date. However, it is best to start on 1 June each year.

During the first period, partial defoliation that removes 25% to 33% of the leaf biomass from grass lead tillers between the 3.5 new leaf stage and the flower stage increases the rhizosphere microbe biomass and activity, enhances the ecosystem biogeochemical processes, and activates the internal grass plant growth mechanisms. Manipulation of these processes and mechanisms does not occur at any other time during a growing season. During the second grazing period, the lead tillers are maturing and declining in nutritional quality and defoliation by grazing is only moderately beneficial to grass development. Adequate forage nutritional quality during the second period depends on the activation of sufficient quantities of vegetative secondary tillers from axillary buds during the first period. Livestock are removed from intact grassland pastures in mid October, towards the end of the perennial grass growing season, in order to allow the carryover tillers to store the carbohydrates and nutrients which will maintain plant mechanisms over the winter. Most of the upright vegetative tillers on grassland ecosystems during the autumn will be carryover tillers which will resume growth as lead tillers during the next growing season. Almost all grass tillers live for two growing seasons, the first season as vegetative secondary tillers and the second season as lead tillers. Grazing carryover tillers after mid October causes the termination of a large proportion of the population, resulting in greatly reduced herbage biomass production in subsequent growing seasons. The pasture grazed first in the rotation sequence is the last pasture grazed during the previous year; i.e. ABC, CAB, and BCA, because the last pasture grazed has the greatest live herbage weight on 1 June of the following season (Manske 2018).

Stocking rates are based on peak herbage biomass on seasonlong grazing practices. The starting stocking rate on the "new" twice-over grazing practice is usually 80% to 100% of the seasonlong stocking rate. It usually requires three grazing seasons with the twice-over strategy stocked at 100% to increase the rhizosphere microbe biomass to be great enough to mineralize 100 lbs/ac of mineral nitrogen (nitrate NO_3 and ammonium NH_4). After the increased rhizosphere microbe biomass can mineralize 100 lbs/ac of mineral nitrogen, the stocking rate can be increased at 10% per year until the system is stocked at 140% of the seasonlong stocking rate. This has been the maximum biological potential reached on North American grasslands from the twice-over rotation strategy.

Once a rotation date scheduled has been determined, do not change that schedule greater than one day for any worldly reason. If you do not like your neighbors bull, build a fence that the bull cannot jump. If you have water sources that sometimes go dry, put in a water tank system on a pipeline. Fix the problems that develop with solutions that do not change the rotation schedule.

Fall Complementary Pasture

The fall complementary perennial grass pasture was Altai wildrye. It could also be a mixture of 50-50% Russian and Altai wildrye with no alfalfa. Russian wildrye does not do well in sandy soil. One pasture was grazed at 1.41 ac/AUM for 30 or 31 days during mid October to mid November. The wildryes are the only perennial grass type in the world that retains adequate nutritional quality to meet a lactating cows requirements during fall grazing from mid October to mid November. Wildryes do not respond well to standard traditional practices. All other grasses grow and behave as if they were types of perennial spring wheat with their physiological mechanisms activated during vegetative growth stages during the spring. The wildryes are different, they all grow and behave as if they were types of perennial winter wheat with their physiological mechanisms activated during the fall and these mechanisms perform in spring only if 50% of the total herbage weight remains at the end of the fall grazing period. If the Altai wildrye produces 3000 lbs/ac of herbage biomass, the plants require that 1500 lbs/ac of herbage biomass remain at the end of grazing in mid November (Manske 2018).

The optional fall complementary pasture could be a monoculture of spring seeded winter cereal planted into cropland, grazed at 0.48 ac/AUM with calf, and divided into four equal pastures separated by electric fence with each pasture grazed for 7 to 8 days with access to previously grazed pastures and a heated water tank at the end of the first pasture grazed. Cattle like winter rye forage more than that of winter wheat, or winter triticale. Purchase your next springs seed during the harvest time of the previous year. Northern Plains elevators rarely hold winter cereal grain very long. At seeding time, do not add much more than 10 to 15 lbs/ac of nitrogen fertilizer, even less if possible.

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Applying the Science to Harvested Forage

Harvested forages appear to be high cost feed when evaluated by the traditional dry matter basis, however, when costs of harvested forages are evaluated by the cost per unit of nutrients, the value of wealth captured from the land natural resources increases. Beef cow-calf producers are the last meat industry to make the switch to nutrient cost diagnostic evaluation.

Old School Updated

Most livestock producers follow the paradigm that the source of wealth from livestock agriculture is the animal weight sold at market. If they had paid attention in high school biology class, they would know this concept is biologically incorrect. Livestock are hetrotrophic herbivores that cannot make their own food from inorganic elements but must ingest organic substances that have been synthesized by autotrophic plants which can produce organic nutrients, like crude protein and carbohydrates, by chemically combining inorganic elements, like hydrogen, carbon, nitrogen, and oxygen, that have been mineralized by soil microorganisms from soil organic matter. These renewable organic forage nutrients are the primary products that produce weight on livestock and are the true source of new wealth from agricultural use of grazingland and hayland resources.

Renewable Forage Nutrients

The major forage produced nutrients are energy (TDN) and crude protein. The energy (TDN) produced by forage plants is part of the ecosystem's carbon cycle. Plants capture and fix carbon from atmospheric carbon dioxide with the hydrogen from soil water during the process of photosynthesis which converts energy from the sun into chemical energy. The assimilated carbon is combined in several ways to form various types of sugars and starches that are collectively the carbohydrates (CHO). These carbohydrates are an energy source for livestock.

Crude protein is deficient in grass lead tillers earlier in the growing season than energy. The crude protein produced by forage plants is part of the ecosystem's nitrogen cycle. Inorganic nitrogen is mineralized from organic nitrogen by numerous soil organisms living in the rhizosphere surrounding living grass plant roots. The inorganic nitrogen is taken up by the roots. The plant combines the inorganic nitrogen with carbon, hydrogen, and oxygen to synthesize different types of amino acids which are then combined to produce various forms of very large organic compounds of proteins. These proteins can be used as enzymes, antibodies, hemoglobin, or to build muscle and increase weight of the livestock.

Capture Greatest Crude Protein Weight per Acre

The paradigm that gains the greatest wealth per acre uses management practices that capture the greatest weight of crude protein per acre. Most livestock producers consider harvested forages to be expensive because the standard harvest technique is to cut the forage plants at the time when the greatest dry matter weight can be captured to get the biggest bale possible. However, harvested forages cut at plant growth stages that yield great amount of forage dry matter and low amounts of crude protein per acre have high costs per pound of crude protein and are high-cost forage feeds that only generate a small portion of the potential new wealth from the land resources. Forage dry matter does not have a real economic value because it is not incorporated into the beef weight produced. The dry matter is simply the carrier of the nutrients it contains. Dry matter is nondigestible and it is deposited on the ground a few days after it is ingested.

Not all harvested forages are high cost feeds. Harvested forages cut at plant growth stages that yield great amounts of crude protein per acre have low costs per pound of crude protein and are low-cost forage feeds that efficiently capture high value from the land natural resources. The renewable forage nutrients are the valuable products produced by forage plants on the land.

Evaluation of Forage Types

Eight forage types were evaluated for costs and returns for 1200 lb cows with mid March calf fed during the 167 day nongraze period from mid November to late April (tables 1, 2, and 3).

The reserved native grassland pasture with no hay management strategy (table 1) used three separate pastures with a total of 34.75 acres allotted per cow, a low production cost of $8.76/ac had a land rent cost of $304.47 and a forage dry matter cost of $116.80/ton. Crude protein at 6%, yield 9.0 lbs/ac at a cost of $0.97/lb. Supplemental crude protein was provided at 0.24 lbs/d at a cost of $12.09. Total forage and crude protein costs were $316.65, or $1.90 per day. Calf fetus and live accumulated weight gain was a mean of 149 lbs with an assumed value at $1.00/lb, the gross return was $149.00 per calf. The net returns after feed costs was a loss of $167.56 per cow-calf pair and a loss of $4.82 per acre. The cost of calf weight gain was $2.12 per pound.

Crested wheatgrass hay cut at the boot stage (table 1) had production costs of $26.50 per acre and forage dry matter costs of $40.77 per ton. Early cut crested wheatgrass hay was fed at 14.0 lbs/day plus 11.0 lbs/day of roughage. The forage from 1.80 acres would cost $47.71 and the roughage would cost $31.62 for a total feed cost of $79.33, or $0.48 per day. Crude protein at 14.5%, yield 189 lbs/ac at a cost of $0.14/lb. Calf fetus and live accumulated weight gain was a mean of 180.50 lbs with an assumed value at $1.00/lb, the gross return was $180.50 per calf. The net returns after feed costs was $101.17 per cow-calf pair and $56.21 per acre. The cost of calf weight gain was $0.44 per pound.

Crested wheatgrass hay cut late at the mature stage (table 1) had production costs of $28.11 per acre and forage dry matter costs of $35.14 per ton. Late cut crested wheatgrass hay was fed at 25.0 lbs/day plus 0.45 lbs/day supplemental crude protein. The forage from 2.59 acres would cost $72.80 and the provided crude protein would cost $22.52 for a total feed cost of $95.32, or $0.57 per day. Crude protein at 6.4%, yield 102 lbs/ac at a cost of $0.28/lb. Calf fetus and live accumulated weight gain was a mean of 180.50 lbs with an assumed value at $1.00/lb, the gross return was $180.50 per calf. The net returns after feed costs was $85.18 per cow-calf pair and $32.89 per acre. The cost of calf weight gain was $0.53 per pound.

Forage barley hay cut early at the milk stage (table 2) had production costs of $68.21 per acre and forage dry matter costs of $28.80 per ton. Early cut forage barley hay was fed at 15.6 lbs/day plus 9.4 lbs/day of roughage. The forage from 0.55 acres would cost $37.18 and the roughage would cost $26.85 for a total feed cost of $64.03, or $0.38 per day. Crude protein at 13.0%, yield 606 lbs/ac at a cost of $0.11/lb. Calf fetus and live accumulated weight gain was a mean of 180.50 lbs with an assumed value at $1.00/lb, the gross return was $180.50 per calf. The net returns after feed costs was $116.47 per cow-calf pair and $211.76 per acre. The cost of calf weight gain was $0.35 per pound.

Forage barley hay cut late at the hard dough stage (table 2) had production costs of $70.35 per acre and forage dry matter costs of $27.40 per ton. Late cut forage barley hay was fed at 21.2 lbs/day plus 3.8 lbs/day of roughage. The forage from 0.70 acres would cost $49.25 and the roughage would cost $13.58 for a total feed cost of $62.83, or $0.38 per day. Crude protein at 9.2%, yield 468 lbs/ac at a cost of $0.15/lb. Calf fetus and live accumulated weight gain was a mean of 180.50 lbs with an assumed value at $1.00/lb, the gross return was $180.50 per calf. The net returns after feed costs was $117.67 per cow-calf pair and $168.10 per acre. The cost of calf weight gain was $0.35 per pound.

Oat forage hay cut early at the milk stage (table 2) had production costs of $69.17 per acre and forage dry matter costs of $29.60 per ton. Early cut oat forage hay was fed at 17.7 lbs/day plus 7.3 lbs/day of roughage. The forage from 0.63 acres would cost $43.43 and the roughage would cost $20.89 for a total feed cost of $64.32, or $0.39 per day. Crude protein at 11.5%, yield 535 lbs/ac at a cost of $0.13/lb. Calf fetus and live accumulated weight gain was a mean of 180.50 lbs with an assumed value at $1.00/lb, the gross return was $180.50 per calf. The net returns after feed costs was $116.18 per cow-calf pair and $184.41 per acre. The cost of calf weight gain was $0.36 per pound.

Oat forage hay cut late at the hard dough stage (table 2) had production costs of $74.53 per acre and forage dry matter costs of $26.40 per ton. Late cut oat forage hay was fed at 23.4 lbs/day plus 1.6 lbs/day of roughage. The forage from 0.70 acres would cost $51.97 and the roughage would cost $11.11 for a total feed cost of $63.08, or $0.38 per day. Crude protein at 7.8%, yield 435 lbs/ac at a cost of $0.17/lb. Calf fetus and live accumulated weight gain was a mean of 180.50 lbs with an assumed value at $1.00/lb, the gross return was $180.50 per calf. The net returns after feed costs was $117.42 per cow-calf pair and $167.74 per acre. The cost of calf weight gain was $0.35 per pound.

Pea forage hay cut at the late growth stage (table 2) had production costs of $86.87 per acre and forage dry matter costs of $37.40 per ton. Late cut pea forage hay was fed at 14.1 lbs/day plus 10.9 lbs/day of roughage. The forage from 0.50 acres would cost $43.45 and the roughage would cost $33.37 for a total feed cost of $76.82, or $0.46 per day. Crude protein at 14.4%, yield 685 lbs/ac at a cost of $0.13/lb. Calf fetus and live accumulated weight gain was a mean of 180.50 lbs with an assumed value at $1.00/lb, the gross return was $180.50 per calf. The net returns after feed costs was $103.68 per cow-calf pair and $195.62 per acre. The cost of calf weight gain was $0.43 per pound.

Low Production Cost is Not Low Cost Forage Feed

Harvested forages have greater production costs than pasture forage, however, the forage production costs do not directly regulate the forage feed costs. This relationship can be demonstrated by a comparison between a harvested forage with high production costs and a pasture forage with low production costs. During the 167 day nongraze period from mid November to late April, forage barley hay cut at the milk stage had high production costs of $68.21 per acre (table 2) and reserved native grassland pasture had low production costs of $8.76 per acre (table 1). Forage barley hay produced 4733 pounds of dry matter and captured 606 pounds of crude protein per acre. The grass pasture had 150 pounds of forage dry matter and captured 9.0 pounds of crude protein per acre. The forage barley hay was feed at 15.6 pounds per day plus 9.4 pounds of roughage per day at a cost of $64.03 per period, or $0.38 per day (table 2). The reserved grass pasture required 34.75 acres plus 40.3 pounds of supplemental crude protein at a cost of $316.56 per period, or $1.90 per day (table 1). Even though the production costs per acre for the reserved grassland pasture were near eight times lower than the production costs per acre for the harvested forage barley hay. The forage feed costs per day for the reserved grassland pasture were five times greater than the forage feed costs per day for the forage barley hay. The net returns per acre for the forage barley hay was $211.76. The net returns per acre for the reserved grassland pasture was $-4.82 (table 3).

The forage barley hay had a crude protein yield of 606 lbs/ac at a cost of $0.11/lb. The reserved grassland pasture had a crude protein yield of 9.0 lbs/ac at a cost of $0.97/lb which required 0.24 lbs of supplemental crude protein per day at a cost of $12.09. The reserved grassland pasture had low quantity of forage weight per acre and very low yield of crude protein per acre which were the primary causes for excessive forage costs and low net returns (table 3).

New Wealth from Forage Nutrients

The renewable forage nutrients produced on the land sustain the growth in weight of livestock. The weight of the calf is the commodity sold at market. The source of calf weight is the forage nutrients. The original source of new wealth generated by livestock agriculture are forage nutrients captured from the land. Generation of greater wealth requires the capture of greater crude protein weight per acre and its conversion into greater calf weight per acre.

The forage types that capture great weight of crude protein per acre are the early cut forage barley, late cut pea forage, and early cut oat forage (table 3). These are also the forage types that generate the greater wealth per acre.

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Table 1. Costs and Returns of native pasture, no hay and perennial grass harvested forage for 1200 lb cow with mid March calf fed during 167 days nongraze period.

Costs/Returns		Native Grass Pasture No Hay	Boot Stage Crested Wheatgrass Hay	Mature Crested Wheatgrass Hay
Forage DM wt	lbs/ac	150.0	1300.0	1600.0
Production Costs	$/ac	8.76	26.50	28.11
Forage DM Costs	$/ton	116.80	40.77	35.14
Crude Protein	%	6.0	14.5	6.4
CP Yield	lbs/ac	9.0	189.	102.
CP Costs	$/lb	0.97	0.14	0.28
Forage/Day	lbs/d	30.0	14.0	25.0
Land Area	ac	34.75	1.80	2.59
supp./Day	lbs/d	0.24	11.0	0.45
Forage Costs	$/p	304.47	47.71	72.80
supp. Costs	$/p	12.09	31.62	22.52
Total Feed Cost	$/p	316.56	79.33	95.32
Cost/Day	$/p	1.90	0.48	0.57
Calf Wt Gain	lbs/p	149.00	180.50	180.50
Wt. Value @$1.00/lb	$	149.00	180.50	180.50
Net Return/c-cpr	$	-167.56	101.17	85.18
Net Return/Ac	$	-4.82	56.21	32.89
Calf Gain Cost	$/lb	2.12	0.44	0.53

Data from Manske 2014, 2019.

Table 2. Costs and Returns of annual cereal and annual legume harvested forage for 1200 lb cow with mid March calf fed during 167 days nongraze period.

Costs/Returns		Milk Forage Barley Hay	Hard Dough Forage Barley Hay	Milk Oat Forage Hay	Hard Dough Oat Forage Hay	Late Pea Forage Hay
Forage DM wt	lbs/ac	4733.0	5133.0	4667.0	5667.0	4650.0
Production Costs	$/ac	68.21	70.35	69.17	74.53	86.87
Forage DM Costs	$/ton	28.80	27.40	29.60	26.40	37.40
Crude Protein	%	13.0	9.2	11.5	7.8	14.4
CP Yield	lbs/ac	606.	468.	535.	435.	685.
CP Costs	$/lb	0.11	0.15	0.13	0.17	0.13
Forage/Day	lbs/d	15.6	21.2	17.7	23.4	14.1
Land Area	ac	0.55	0.70	0.63	0.70	0.50
supp./Day	lbs/d	9.4	3.8	7.3	1.6	10.9
Forage Costs	$/p	37.18	49.25	43.43	51.97	43.45
supp. Costs	$/p	26.85	13.58	20.89	11.11	33.37
Total Feed Cost	$/p	64.03	62.83	64.32	63.08	76.82
Cost/Day	$/p	0.38	0.38	0.39	0.38	0.46
Calf Wt Gain	lbs/p	180.50	180.50	180.50	180.50	180.50
Wt. Value @$1.00/lb	$	180.50	180.50	180.50	180.50	180.50
Net Return/c-cpr	$	116.47	117.67	116.18	117.42	103.68
Net Return/Ac	$	211.76	168.10	184.41	167.74	195.62
Calf Gain Cost	$/lb	0.35	0.35	0.36	0.35	0.43

Data from Manske 2014, 2019.

Table 3. Evaluation of forage type by quantity of value captured from land natural resources during 167 day nongraze period.

Forage Type	Crude Protein Yield lb/ac	Crude Protein Cost $/lb	Land Area ac/c-cpr	Calf Wt Cost $/lb	Forage Feed Cost $/c-cpr	Net Return $/ac
Forage Barley Milk	606	0.11	0.55	0.35	64.03	211.76
Pea Forage Late	685	0.13	0.50	0.43	76.82	195.62
Oat Forage Milk	535	0.13	0.63	0.36	64.32	184.41
Forage Barley Hard Dough	468	0.15	0.70	0.35	62.83	168.10
Oat Forage Hard Dough	435	0.17	0.70	0.35	63.08	167.74
Crested Wheat Boot	189	0.14	1.80	0.44	79.33	56.21
Crested Wheat Mature	102	0.28	2.59	0.53	95.32	32.89
Grass Pasture No Hay	9	0.97	34.75	2.12	316.56	-4.82

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2021 Acid Soil Management with Hard Red Spring Wheat

Ryan Buetow

Hard Red Spring Wheat (HRSW) yields are decreasing due to acidic soils. No-till practices paired with heavy N use have lowered the soil pH on many acres of the Northern Great Plains. Acid soil where the pH drops below 5.5 has an impact on nutrient availability, soil microbial activity, stunted roots from aluminum (Al) toxicity and other plant/soil interactions. These areas can be improved from surface liming; however, liming can be costly. For many producers facing this issue, especially those working rented land, there is a search for alternative options to reduce yield loss on acidic ground. Research has been conducted in western North Dakota on adaptive management strategies for mitigating the symptoms of aluminum toxicity and soil acidity including variety selection, in-furrow fertilizer application, and seed treatments. Variety selection showed a significant difference in yield (Table 1). In a trial focusing on in-furrow treatments, interactions were found among variety, biochar application, and in-furrow phosphorus. It was observed that a susceptible variety of Hard Red Spring Wheat (SY Soren) had a yield response to in-furrow phosphorus (P), where a tolerant variety (Lanning) did not respond to in-furrow P (Table 2). Calcium in-furrow did not have an impact on yield. Across HRSW varieties a yield bump of 1.5 bushel was shown from seed placed P (0-45-0) applied at high rates (60 lb P_2O_5/ac) (Table 3). This mechanism doesn't appear to be as strong for HRSW as shown in similar durum trials. A yield reduction from biochar was identified with the control yielding 24 bushels/ac and a rate of 8 lbs/ac seed placed yielded 17.6 bushels/ac. This trial is planned to be repeated in 2022 to hopefully separate out the influence of drought. The 2021 data suggests use of tolerant HRSW varieties along with in-furrow P fertilizer to alleviate symptoms of an acid soil. Ideally producers should be applying tons of lime to bring the pH above 5.5 because the variety and fertilizer may fix the yield loss but does not fix issues with pesticide breakdown and carryover, soil microbiological activity, and nutrient tie-up; all issues caused by acid soil. This issue is in more than a small pocket of North Dakota and is facing fields across the state as shown in the 2021 sunflower survey data (Figure 1).

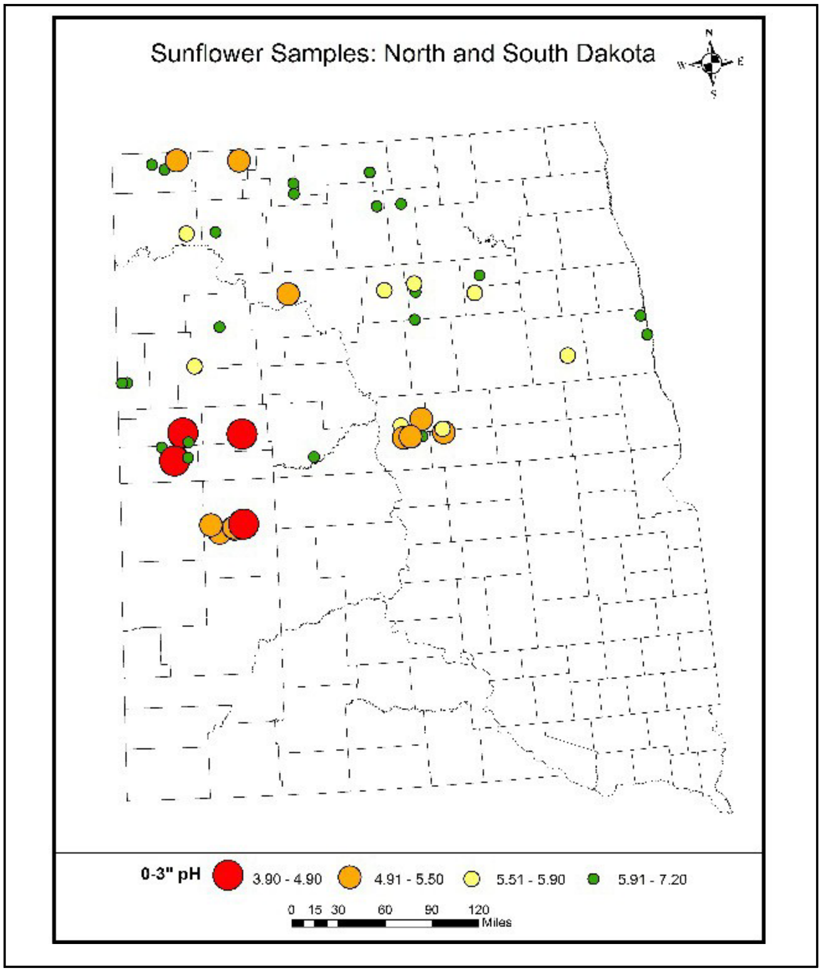

Figure 1. 0-3" soil samples taken in 2021.

Table 1. Variety yield data across locations 2021.

Variety	**Dickinson**	**Minot**	**Lefor**
		bu/ac	
Bolles	18.0b	36.0	57.3
CP3099A	**23.0**	**47.2**	-
CP3119A	**22.6**	**47.3**	**69.3**
CP3188	**21.8**	**42.3**	65.4
CP3530	**19.9**	34.0	-
CP3915	17.4	**39.7**	64.4
Dagmar	**22.6**	37.2	64.2
Duclair	**20.2**	**41.6**	61.5
Glenn	18.6	34.4b	60.4
Lanning (tolerant check)	**20.5**	**47.9**	64.8
SY Soren (susceptible check)	**19.2**	**39.6**	61.9
TCG Heartland	15.8	**39.6**	62.3
TCG Spitfire	**20.8**	**42.4**	**72.6**
WB9479	12.7	**41.8**	61.8
WB9516	13.1	**46.4**	**68.4**
WB9590	13.2	**39.6**	66.8
WB9606	**21.4**	**39.0**	67.4
WB9719	11.2	**44.5**	**70.8**
LSD (0.05)	3.9	10.7	4.2

Table 2. In-furrow fertilizer treatments in Dickinson 2021.

In-furrow treatment	Variety	
	Soren (susceptible)	Lanning (tolerant
Control	21.4bc	25.7a
Control+biochar*	15.3e	18.1d
Phosphorus	25.1a	24.0ab
Phosphorus+biochar*	16.2de	21.0c
LSD (0.05)	2.6	

*biochar was placed in furrow at a rate of 8lbs/ac

Table 3. P fertilizer across varieties, Dickinson 2021.

Treatment	Yield
Control	20.1b
60 lbs additional P	21.6a

2021 National Sunflower Production Survey

Ryan Buetow, Febina Mathew, Jarrad Prasifka

Overview

Starting in 2001 the National Sunflower Association coordinated a field survey that not only looked at yield, but also agronomic factors affecting yield and factors that limited yield such as disease, insects, and weeds that occurred in each field. That survey has continued initially every year, and starting in 2013, every other year. During the 2021 sunflower growing season, trained teams, including agronomists, entomologists, pathologists, and Extension agents, surveyed fields across North Dakota, South Dakota, Minnesota, Kansas, Colorado, Texas and Nebraska (figure 1). A majority of the fields surveyed were in North Dakota with 79 completed surveys and South Dakota with 52 completed surveys with a total of 164 fields surveyed.

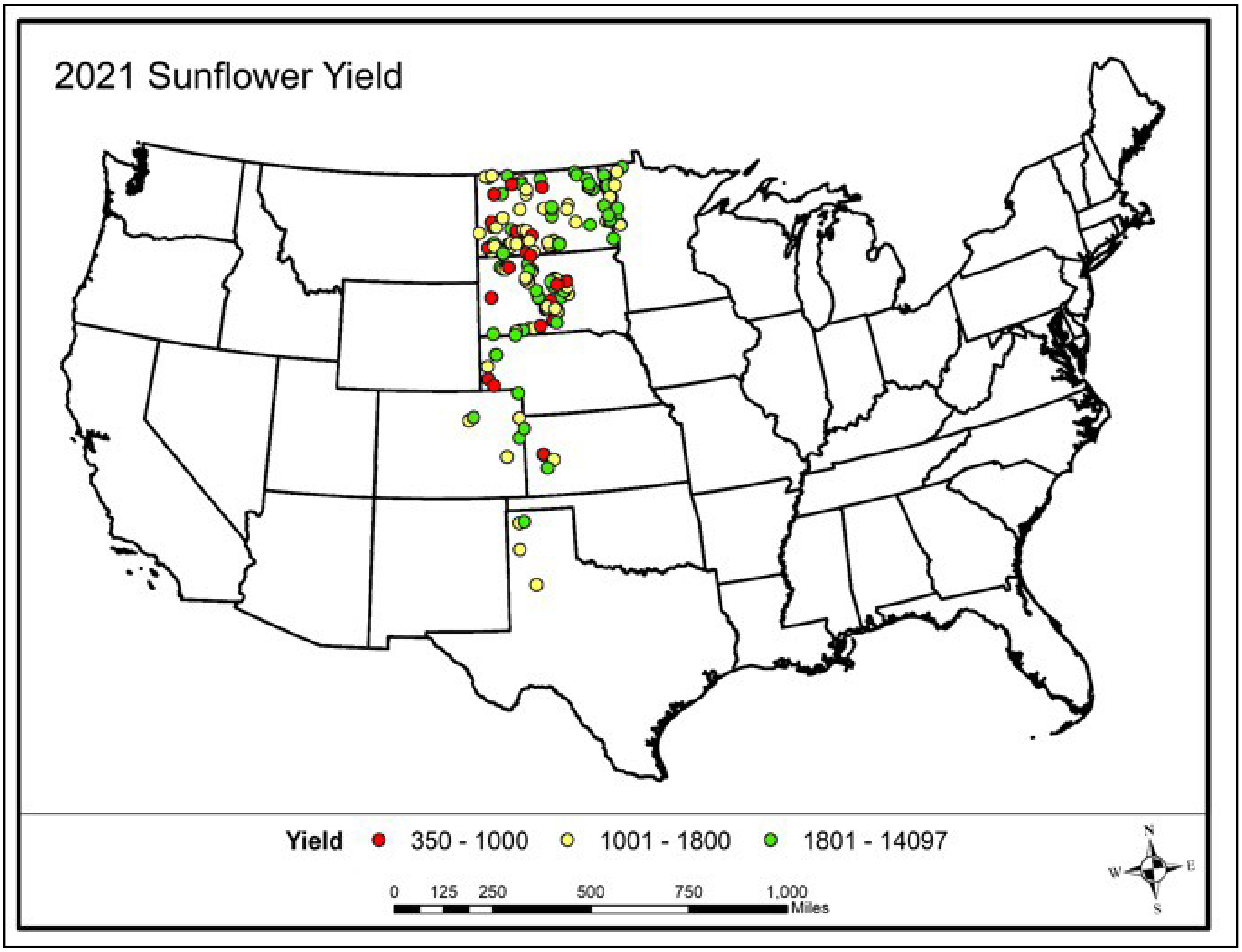

Figure 1 Sunflower survey locations in 2021.

Management and yield factors

Each team evaluated plant stand, yield potential, disease, insect, and weed issues for each field. A yield estimate was calculated based on plant stand, head size, filling of the head, seed size, percent filled seeds, and percent loss due to bird feeding. The 2021 average surveyed sunflower yield across completed surveys was 1,630 lbs/acre across states with an average stand of 15,066 plants/acre. North Dakota estimated yield averaged 1,553 lbs/acre (Figure 2), lower than the 2019 average of 1,781 lbs/acre.

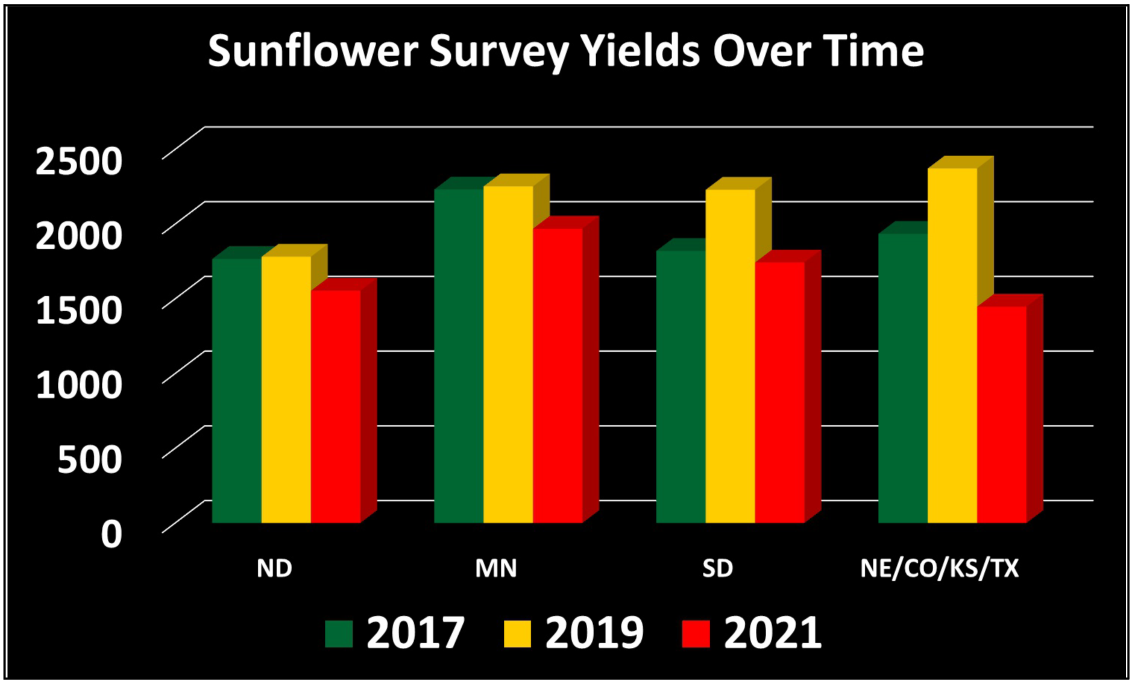

Figure 2 Sunflower yield over time by region.

While 2017 and 2021 would be considered drought years with a majority of all fields surveyed claiming drought as the number 1 factor with 51%, the opposite was an issue in 2019. With excessive moisture in 2019 disease was a major issue across many surveyed fields with 25% of the 133 total fields considering it a number one factor (Table 1). Plant spacing within the row has been a consistent issue across survey years. Across all surveyed fields 9% had plant spacing as the number one factor, 9% no problem, and 7% disease.

Table 1. North Dakota and South Dakota #1 yield limiting factors noted in the 2017, 2019, and 2021 surveys.

Yield Factor	North Dakota #1 limiting factor			South Dakota #1 limiting factor		
	2017	2019	2021	2017	2019	2021
	%					
Disease	17	21	6	9	21	4
Plant spacing	10	12	10	24	28	8
Lodging	3	13	3	4	3	0
Drought	32	1	47	40	0	63
Weeds	12	1	1	0	3	2
Insects	1	6	3	2	10	0
Birds	9	11	10	0	7	2
Uneven growth	3	0	1	4	3	0
Other	6	15	1	0	0	0
No Problem	5	6	23	7	14	0

Disease

With dry conditions across a large portion of surveyed fields there was much less incidence of most diseases compared to other years. Prevalent diseases noted this year were sclerotinia, rhizopus, Phomopsis (figure 3), and phoma.

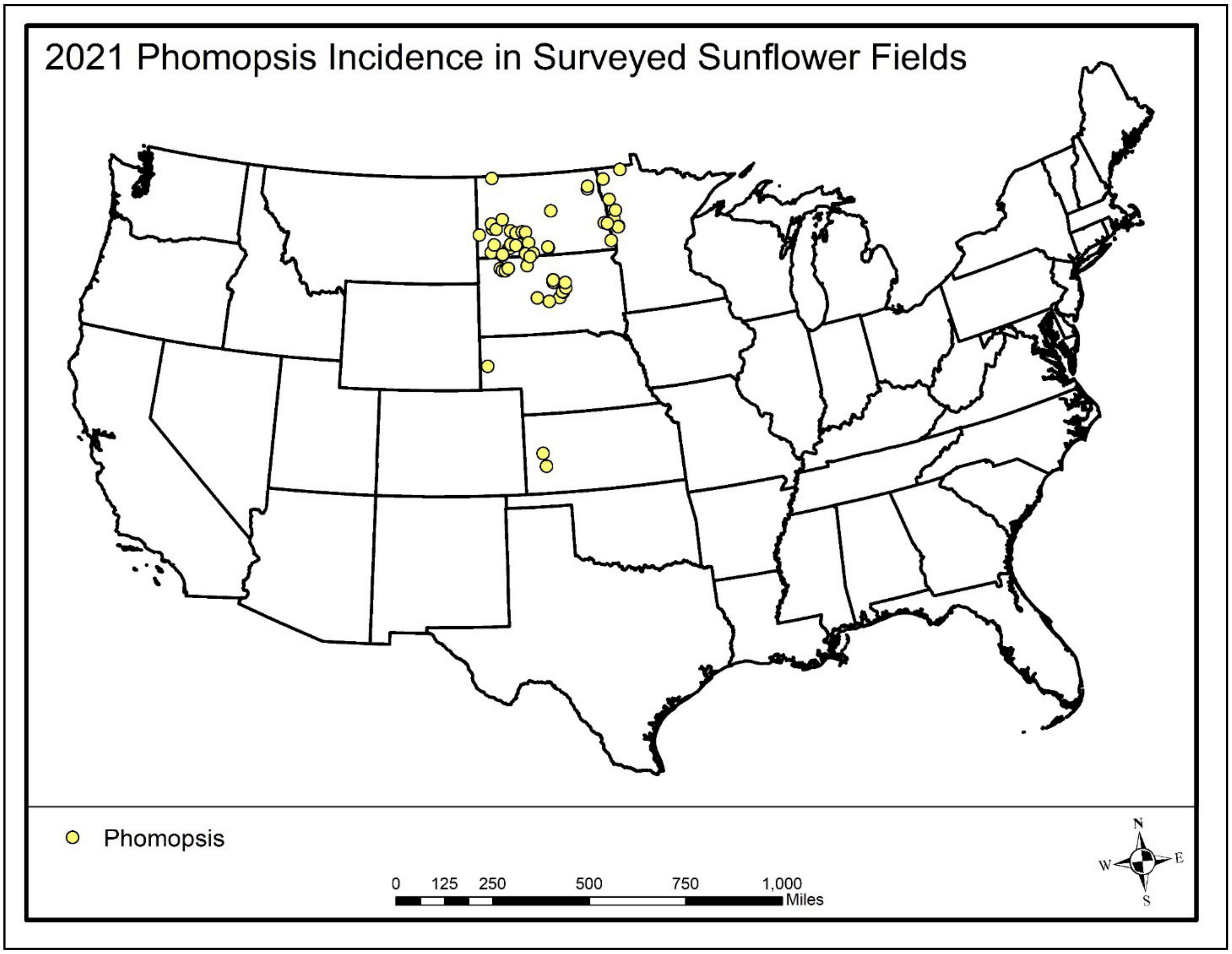

Figure 3 Phomopsis incidence across surveyed area.

Soil pH

A new factor observed in selected fields was soil pH in the top 3 inches of the sunflower field. Composite 0-3" soil samples were taken from fields and analyzed for pH (figure 4). Stratified soil acidity is becoming an issue across the great plains in reduced tillage systems. Of the fields sampled 33% returned a pH below 5.5. Of those fields 80% were observed as no-till, 13% as min-till, and 7% as conventionally tilled.

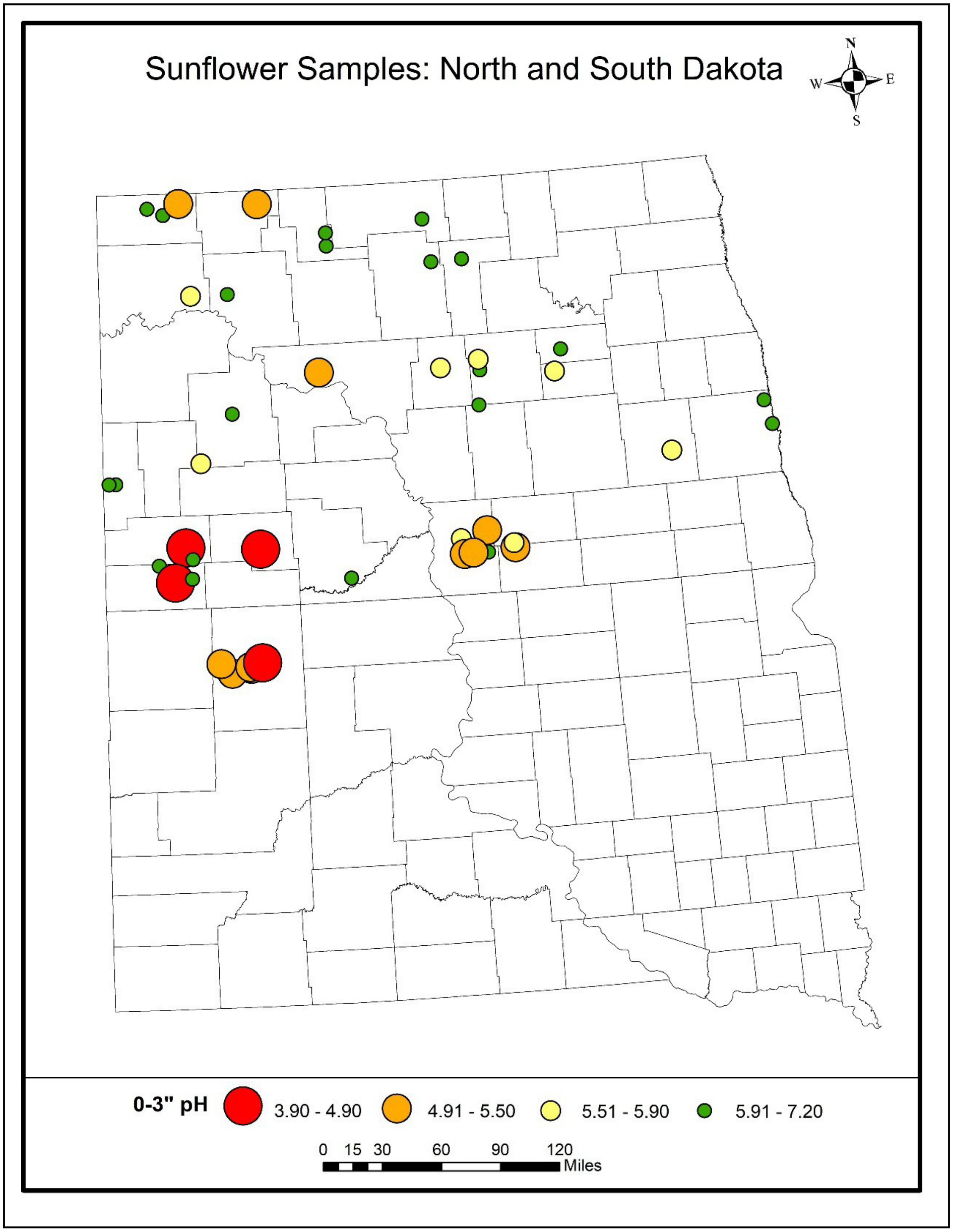

Figure 4 0-3" soil pH in surveyed fields.

Phomopsis stem canker

A total of 300+ stalks from 64 fields (5 to 6 stalks per field) were received from NSA surveyors, extension agents and farmers (6 counties in MN, 17 counties in ND, 12 counties in SD, 3 counties in NE, 2 counties in CO). To identify the fungi causing Phomopsis stem canker, DNA was extracted directly from the stalks and subjected to the qPCR assay developed by Elverson et al. (2020). Both *D. gulyae* and *D. helianthi* were detected in the plant samples obtained from the five U.S. states (Figure 5).

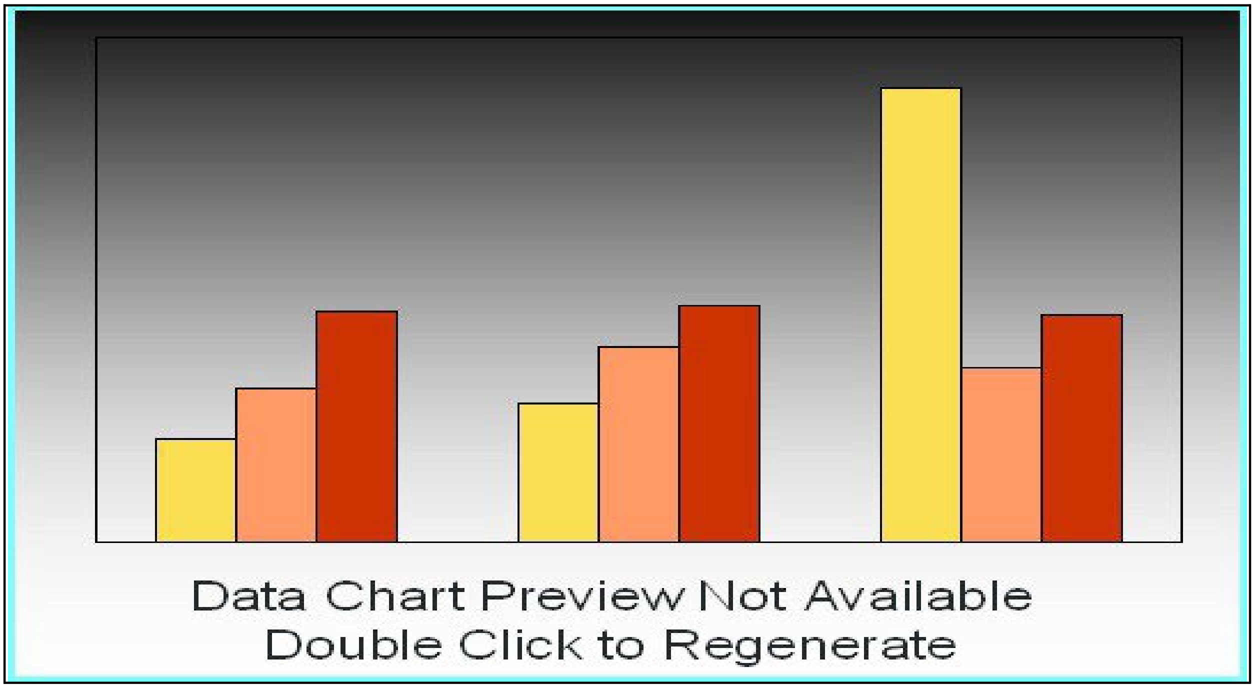

Figure 5. Percent pathogen prevalence by U.S. state.

Insects

As in previous years of the NSA Sunflower Production Survey, insect data include two different types of evaluation; in-field assessments for several secondary pests, and lab-based evaluation of damage for seed samples sent to the USDA lab in Fargo, ND. The in-field assessments include sunflower midge, sunflower bud moth, sunflower seed maggot and Dectes stem borer. These data are useful, but have at least two limitations. First, for the midge, bud moth, and seed maggot, survey participants are looking at symptoms (not living insects) that primarily include head deformation, so damage from each of these insects can be confused with one another or with other causes of head deformity. Second, the frequency (% damaged plants) does not provide information on severity of damage or yield effects. Data on bird losses (in-field) are an exception to the use of indirect measures for in-field data collection. The lab-based evaluations of seed samples give more direct estimates of damage. Using X-ray images, damage to seeds is measured for 100-seed samples and assigned either to weevils (red sunflower seed weevil) or caterpillars (larvae of banded sunflower moth or sunflower moth). For confection seeds, these plants are also dehulled and visually scored for “brown spot” damage by Lygus bugs.

Data from in-field assessments are summarized in ***Table 2*** (2021) and ***Table 3*** (2019).

Table 2: Percent loss (birds) or presence of insect pests in NSA survey fields, 2021.

2021	Birds	Midge	Seed maggot	Bud moth	Dectes	# of fields
Texas	1	0	0	0	18	4
Kansas	0	0	0	0	96	5
Colorado	0	0	0	0	49	7
Nebraska	0	0	0	0	0	5
South Dakota	3	1	6	1	29	52
North Dakota	3	9	2	2	21	79
Minnesota	3	11	0	0	0	12
Manitoba	0	0	0	0	0	0

Table 3: Percent loss (birds) or presence of insect pests in NSA survey fields, 2019.

2019	Birds	Midge	Seed maggot	Bud moth	Dectes	# of fields
Texas	0	0	0	0	0	0
Kansas	0	0	0	0	48	5
Colorado	0	0	0	0	4	5
Nebraska	0	0	0	0	0	4
South Dakota	2	3	7	3	13	29
North Dakota	4	11	6	3	13	84
Minnesota	0	0	0	0	0	6
Manitoba	0	0	0	0	0	0

Data from 2021 and 2019 show losses from birds and damage by sunflower midge, sunflower bud moth, and sunflower seed maggot are relatively low and largely confined to South Dakota and North Dakota, and Minnesota. Dectes stem borer, while apparently increasing in South Dakota and North Dakota, is more common in southern areas like Texas, Kansas and Colorado. Compared to 2019, it does appear that there was a increase in frequency of damage by Dectes stem borer in 2021. It is not clear what effect this had on yields or what might have produced the apparent increase; lodging in survey fields with very high Dectes infestations (at least 80% stems infested; n = 19 fields) was low (2.37%) and not significantly greater than (1.79%) lodging in 71 fields with no Dectes larvae detected.

Data from seed samples evaluated at the USDA in 2021, 2019 and 2017 are summarized in **Figure 6**.

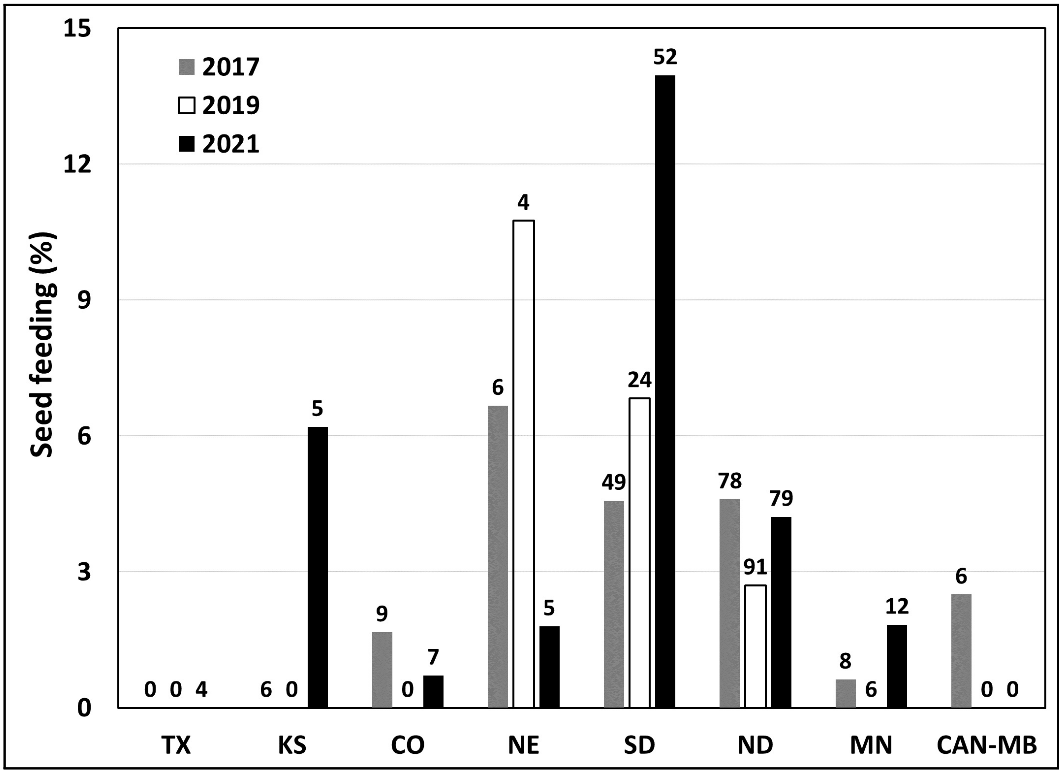

Figure 6. Percent insect-damaged seed by state. Number of fields shown over each column.

Increased damage in the second most-sampled state (SD) brought the overall average amounts of seed damage up from 3.7% (2019) to 7.2% (2021). By pest, the majority of seed damage was caused by the red sunflower seed weevil, far more than that caused by banded sunflower moth and sunflower moth.

Lygus damage (i.e., kernel brown spot damage) to confection seed was low (less than or equal to 1% for 13 of 15 fields).

The last general trend was a higher number of very heavily damaged (> 20% insect-damaged seed) fields versus the previous survey. In 2019, only 1 of 120 fields sustained >20% damage, while in 2021 heavy damage was seen in 26 of 207 fields. It is not clear why this was the case; it seems that mild winter conditions can allow pest (especially seed weevils) populations to be unusually high in the following summers. There are also several other possible explanations that cannot be evaluated without at least some additional data from the most heavily-damaged areas.

Surface Lime Impacts on No-Till North Dakota Soils

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Objective

Soils become acidic from the mineralization of ammonium-based fertilizers. No-till soils are particularly susceptible to acidification from the lack of mixing subsurface alkaline products and the tendency to apply ammonium-based fertilizers at or near the soil surface. As a result, the zone of acidification is at the depth of fertilizer placement (Blevins et al., 1982; Dick, 1983).

Soil pH controls chemical weathering and soil solution chemical activity. Phosphorus (P) and aluminum (Al) are two elements that greatly impact crop production and are dependent on soil pH. Phosphorus is most readily plant available when the soil pH is approximately six to seven. When soil pH is less than 5.5, Al becomes soluble, binds to P, and renders P unavailable to plants. Additionally, Al can have a toxic effect to plants that stunt and deform root growth and reduces seed germination. Free Al in the soil solution hydrolyzes water which further acidifies the soil (Lindsay, 2001). Soil pH less than 5.5 can reduce bacteria activity and cause crop nitrogen deficiencies (Graham, 1992).

Calcium-carbonate (lime) neutralizes acidity and is a common liming amendment (Sims and Lamb, 2010). Agriculture lime is not readily available in North Dakota. However, a waste product of the sugarbeet refining process (SBWL) is comprised of lime (Sims, 1996).

Lime requirement recommendations have not been developed for North Dakota (Sims, 1996). Soil acidity is new and growing issue to North Dakota soils. This project investigated the impacts of surface applied SBWL on acidic no-till soils in North Dakota.

Methodology

Eleven sites (Figure 1) were established in April/May of 2021 after planting. Soil pH at the 0-3 in depth was less than 5.5. Collaborating producers planted and managed their crop. Experimental design was a randomized complete block design.

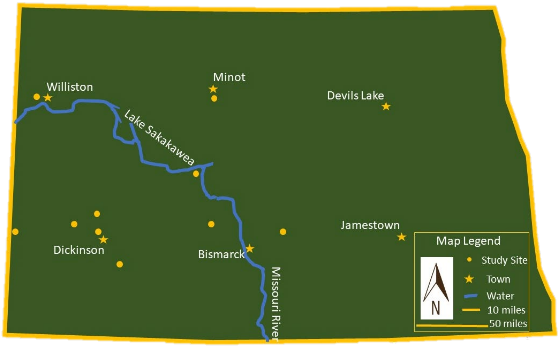

Figure 1. Locations of experimental sites in North Dakota (Google LLC, 2022).

Plastic hoops with a 36 in diameter were placed in the field and spaced at least 10 ft away from adjacent hoops. Soils were collected within 1 ft outside of the hoop. Soil was sampled by a hand probe at the 0-3, 3-6, and 0-6 in depths. Sugarbeet waste lime treatments were hand applied within the hoop after initial soil sampling. Treatments were 0, 2, 4, 8, and 16 tons lime/ac. The SBWL contained 0.6 lbs nitrate/ton, 5.2 lbs P/ton, 0.9 lbs potassium/ton, 75.5 % calcium carbonate equivalence, and 14% moisture.

Post harvest, October/November, soil samples were collected by a hand probe within the hoop at the 0-3, 3-6, and 0-6 in depths.

Soils were analyzed for nitrate, Olsen P, potassium, calcium carbonate equivalent, pH, buffer pH, salinity, organic matter, cation exchange capacity, zinc, sodium, manganese, magnesium, aluminum. Soil analysis was completed by AGVISE LABORATORIES (2022). Comparison of means and regression analysis was conducted by Statistical Analysis Software (SAS Institute Incorporated, 2019).

Results

Sugarbeet waste lime treatments increased the soil pH of the 0-3 and 0-6 in depths. Lime applications of 4, 8, and 16 tons/ac increased the 3-6 in soil depth (Table 1).
The regression analysis procedure produced statistically significant polynomial regressions from all, except the 6.3 and 7.1 buffer pH soil environments (Table 2).
Sugarbeet waste lime treatments impacted salinity, P, Ca, Mn, Al, and calcium-carbonate-equivalent (Table 3). However, SBWL treatments did not impact soil organic matter (p-value 0.955), nitrate (p-value 0.703), potassium (p-value 0.983), magnesium (p-value 0.799), zinc (p-value 0.888), sodium (p-value 0.698), and cation exchange capacity (p-value 0.995). The 4, 8, and 16 tons lime/ac treatments increased soil salinity (Table 3).

Table 1. Beet lime impacts on soil pH at various depths.

Lime tons/ac*	0-3in	3-6in	0-6in
	----------pH----------		
0	5.4e	6.0d	5.7e
2 (2.6)	6.0d	6.0d	5.9d
4 (5.3)	6.4c	6.2c	6.3c
8 (10.6)	6.7b	6.4b	6.7b
16 (21.2)	7.0a	6.7a	6.9a
P-value	<0.001	<0.001	<0.001
Variance	0.609	0.461	0.528
C.V.	4.28	6.5	5.3

*Applied as tons of lime/ac. Parentheses values are tons of SBWL/ac.

Table 2. Regression analysis and predicted lime needed to raise soil pH at the 0-3 inch depth.

Buffer pH‡	Desired pH (0-3 in depth)			Equation**	r^2
	5.5	6	6.5		
	Tons of Calcium Carbonate/Acre				
6.2 n=5†	5.6	9.5	14	$y = 1.271x^2 - 6.8828x + 5.0276$	0.99*
6.3 n=7	10	11	8.5	$y = -7.0431x^2 + 82.954x - 233.15$	0.6
6.4 n=20	0.7	3.4	8.6	$y = 5.1047x^2 - 53.374x + 139.86$	0.81*
6.5 n=24	2.7	5.2	8.6	$y = 1.5829x^2 - 13.1x + 26.826$	0.60*
6.6 n=29	2	4.5	8.1	$y = 2.0756x^2 - 18.833x + 26.826$	0.67*
6.7 n=19	1.5	5.5	9.2	$y = -0.6377x^2 + 15.394x - 63.884$	0.57*
6.8 n=27	0.9	2.4	5.1	$y = 2.3551x^2 - 24.025x + 61.806$	0.54*
6.9 n=22	0.1	1.2	3.8	$y = 2.9871x^2 - 32.222x + 86.998$	0.61*
7.0 n=16	-0.1	0.5	2.5	$y = 2.9062x^2 - 32.259x + 89.428$	0.59*
7.1 n=5	1.1	4.2	7.3	$y = -0.1207x^2 + 7.6291x - 37.184$	0.56

*r^2 was significant at the 0.05 level.

**x variable is desired soil pH at the 0-3 in depth. y variable is tons of lime/ac.

†n is the number of samples from each soil environment.

‡Sikora, 2006.

Table 3. Beet lime impacts on soil nutrients at the 0-6 inch depth.

Lime	Salts	Phosphorus (Olsen)	Calcium	Manganese	Aluminum	Calcium Carbonate Equivalence
tons/ac*	mmhos/cm			ppm		%
0	0.3b**	18d	1781c	18a	5a	0.6c
2(2.6)	0.3b	19d	1999c	14ab	2b	0.6c
4 (5.3)	0.4ab	20c	2286c	11ab	2b	0.8b
8 (10.6)	0.5a	23b	3096b	9b	2b	1.0b
16 (21.2)	0.5a	26a	4143a	9b	1b	1.5a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Variance	1.18	56.7	1,480,729	54.56	15.1	0.28
C.V.	39.4	33	32.8	54.5	157.3	44.5

*Applied as tons of lime/ac. Parentheses values are tons of SBWL lime/ac.

**Different letters indicate statistical differences at the 0.05 level.

Conclusions & Implications

- Surface applied SBWL could improve crop yields from by increasing the soil pH and by reducing Al and Mn.
- The regression equations (Table 2) based on the initial buffer pH (Sims, 1996) can be used to guide producers on lime recommendations. Soil buffer pH values of 6.1 or less and 7.2 or greater were not collected in this study.
- All pH buffer tests were greater than 6.3 and indicates that the reserve acidity pool is relatively small (Sims, 1996). Liming these soils to desirable pH levels (i.e. pH 6) could be required once a decade or more. Saskatchewan research suggests that similarly cropped, fertilized, and limed soils acidify in 18 years (Curtin and Ukrainetz, 1997).
- Olsen P soil tests increased from SBWL applications (Table 3). Sugarbeet waste lime in an acid soil environment might serve as P fertilizer.
- Soil salinity increased from SBWL (Table 3). However all treatments were less than 0.5 mmhos/cm and likely would not negatively impact North Dakota crop yields (Franzen et al., 2019).

- Calcium increased from SBWL applications (Table 3). Manganese and soil extractable Al levels decreased from SBWL treatments. Lime increased the soil pH and likely rendered Mn and Al insoluble (Lindsay, 2001).
- Two and 0 tons of lime/ac treatments both had 0.6% calcium-carbonate equivalence (Table 3). This suggests that the 2 tons of lime/ac reacted with the soil in one growing season.

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Surface Applied Super-U Impacts on Two-row Barley Yield and Quality

Chris Augustin, Director – Dickinson Research Extension Center

Introduction

A barley nitrogen trial sponsored by the North Dakota Barley Council was conducted in 2021 near Belfield. This

Materials and Methods

Field plots were 10 feet wide and 40 feet long with 10 foot buffers between each plot. There were six replications and the experiment was arranged as a randomized complete block design. AAC Synergy barley (two-row) was planted on April 27, 2021 at a rate of 900,000 live plants per acre with an Amity single disc no-till drill. The initial soil test revealed 17 lbs nitrogen/ac and 70 lbs/ac of 11-52-0 fertilizer was mid-row banded at planting. Super-U was hand applied three days after planting. Super-U is a urea fertilizer treated with the nitrogen stabilizing products DCD and NBPT. Plots were combined on August 20, 2021.

Results

Nitrogen treatments did not impact barley yield, protein, or test weight (table 1). The grain yield ranged from 8.9 to 13.6 bu/ac. Barley protein content was extremely high and ranged from 17.8 to 19.4 percent. Barley test weight ranged from 45.1 to 46.5 lbs/bu.

Table 1. Impacts of nitrogen treatments on barley yield, protein, and test weight.

Treatment (lbs nitrogen/ac)	**Yield (bu/ac)**	**Protein (%)**	**Test Weight (lbs/bu)**
Check (25)	13.6	17.8	45.7
50	12.3	18.5	45.6
75	8.9	18.5	45.3
100	10.3	18.7	45.1
125	11.8	18.2	45.2
150	13.6	18.6	45.7
175	10.4	19.4	46.5
P-Value	0.3625	0.4106	0.2472
Variance	16.73	0.91	0.98
Coefficient of Variation	35.4	2.1	5.3

Summary

Barley did not respond to nitrogen treatments. The drought of 2020 and 2021 likely impacted the yields.

Effect of a single-TAI and delayed feedlot entry program on reproductive performance and profitability
and
Beef cattle producer heifer development survey results for 2021

Douglas Landblom
Dickinson Research Extension Center

Project Brief:

Alternatives to encumbering more rented land and chasing economies of scale shift and redirect thinking toward conducting enterprise analysis scenarios to determine, "What can be done with the farm we have?" Drawing together strengths of more than one enterprise in which complementarity capitalizes on component feedback consistently results in enterprises being stronger and more efficient than when managed independently as stand-alone enterprises. Case in point, crop and beef cattle production businesses are for the most part managed as separate entities. But when managed together, capitalizing on annual forage grazing of forages grown on cropland, the net return per land unit is greater. Melding multi-faceted management strategies within the beginning to small and medium sized farm base provides the farm manager greater flexibility and internal control over multiple activities and associated expenses. Strategies of importance relative to complementing systems include reproductive efficiencies, multi-crop grain-oilseed-forage rotations, animal growth profile manipulation, growing animal muscle-marbling enhancement, delayed feedlot finishing growth and feed efficiencies, and greater ending hot carcass weight and more system net return. To new and established small to medium sized farm managers, reproductive efficiency improvement begins with accessing the merits of artificial insemination, i.e., 1) Reproduction is the most profitable single management tool for the beef cattle enterprise, 2) heifers that calve early with their first calf (first 21 days of the calving season) produce more pounds of beef compared to their later calving counterparts, 3) Heifers that calve early with their first calf have greater herd longevity and lifetime productivity, 4) accessing elite sires artificially insures replacement heifers have above average production potential, and 5) replacement heifers bred to elite sires replace themselves with enhanced genetic potential.

Proven by a large body of reproductive management research, "Why are only less than 10% of breeding age females in the U.S. beef cattle herd bred artificially? Because, although reliable proven estrus synchronization protocols put breeding by appointment at the cattleman's fingertips, preparing any group of females for appointment breeding is labor intensive. Nonetheless, cattlemen who know the value of focused time for appointment TAI make the necessary labor commitment and actually lower their breeding cost per pregnant female, because bull semen cost per pregnant female has not increased appreciably over time compared to the average herd bull cost per pregnant female. Multi-crop rotation efficiencies that include low C:N ratio cover crop mixes contribute to increased soil organic matter, which in turn, feeds soil microbial populations resulting in improved plant nutrient mineralization, i.e., 16.9% increase in mineralized N for each 1.0% increase in soil organic matter (Cihacek et al., 2018). Yearling steers grazing native range and crop rotation annual forages (pea-forage barley mix, forage corn, 7 to 13-specie cover crop mix) for >200 days during the growing season contribute organic matter to the integrated system. When beef efficiency grazing annual forages in a crop rotation is contrasted with growing grain corn in the semi-arid region of the northern Great Plains, beef produced per land unit exceeds that of dryland corn per land unit. And slower steer growth over the 200^{+} grazing days of approximately 2.34 pounds per day results in compensating gain during finishing, significantly better feed efficiency, and heavier hot carcass weight resulting in greater system carcass net return. Coalescing heifer development and downstream efficiencies, new and established small to medium-sized mixed crop and beef cattle ranches can capitalize on efficiency potential by combining activities using AI and appointment breeding to ensure heifers enter the cow herd calving early with their first calf and not using cleanup bulls but turning the non-pregnant heifers into extended grazing yearling feeder heifers for delayed feedlot entry finishing.

Integrated crop-livestock beef cattle systems research at the North Dakota State University, Dickinson Research Extension Center (DREC), has shown that regardless of steer frame score extended grazing of perennial and annual forages and delayed feedlot entry supported comparable meat quality and was consistently more profitable than feedlot control steers (Senturklu et al., 2018; 2019). This previous yearling steer grazing performance would be nutritionally supportive and is an ideal platform for replacement heifer development. First service TAI using a 14-day Controlled Internal Drug Release® (CIDR)-PGF2α (PG)-66-hour TAI ± 2 hours results in consistent pregnancy rates of 50-60% (Perry et al., 2012, 2015). A principal result from the use of progesterone delivered from a CIDR is to manipulate follicular waves by preventing the negative effect of premature $PGF_{2\alpha}$ release from the uterus on corpus luteum survival (Patterson et al., 2019. For virgin heifers, a 14-d CIDR followed by $PGF_{2\alpha}$ 16 d after CIDR removal and GnRH at the time of insemination 66 hr.±2hr after $PGF_{2\alpha}$ administration has been a cost-effective TAI program. Heifers that conceive and become pregnant at the first service have a greater probability of becoming pregnant early in subsequent breeding seasons (Burris and Priode, 1958). Research has shown that females conceiving early in the breeding season and calving during the first 21 days of the calving season have increased longevity compared to those that calve in the second 21 days or later (Cushman et al., 2013). Moreover, using a single-TAI procedure produces heifers that are timed to calve early and the cost for keeping easy-calving heifer bulls year-around is eliminated.

For this long-term research and extension project, the following outcomes include: 1) establish a single-TAI heifer development system in which non-pregnant heifers become grazing stocker feeder, 2) commit non-pregnant stocker heifers to a long-term extended grazing protocol grazing multi-crop rotation annual forages, 3) increase producer awareness and knowledge of attainable efficiencies when single-TAI and extended grazing systems are merged, 4) increase stakeholder awareness of retained ownership, finishing economics, extended grazing efficiency effect on hot carcass weight, quality grade, and premiums and discounts, 5) train new and established small to medium-sized farmer-ranchers estrous synchronization management techniques and cattle artificial insemination, and 6) increase understanding for the value of using elite AI sires for genetic enhancement by retaining heifer calves.

The first breeding and finishing of non-pregnant heifers has been completed as well as completion of beef cattle producer synchronized heifer development surveys. Therefore, a limited amount of data is available at this time from which to make definitive conclusions related to success and profitability. Preliminary data will be presented during the program.

Beef cattle rancher heifer synchronization survey results are shown in the table below.

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2021 Rancher Timed AI Heifer Synchronization Project – SUMMARY
Dickinson Research Extension Center

	DRYLOT	GRAZING
Number of Systems	3 Drylot	3 Grazing
TMR		
Lb/Hd/Day	25.7	
Cost/Ton	$58.15	
Suppl/Lb/Hd/Day	2.17	
Grazing		
Tame Gras & Native Range	-	
Cost/Ac	-	$16.67
Cost/Day	-	$0.90
Pasture Yield, T/Ac	-	0.567
Vaccine Cost (Range $1.91 - $11.56)	8.29	5.88
Synchronization		
No. Synchronized	133	52
TAI Pregnancy	56%	74%
Repeat Pregnancy	47.2%	-
TAI + Repeat Pregnancy	75.5%	-
Bull Bred	16.7%	-
Open	7.81%	-
Semen Cost		
Average Semen Cost	$21.33	$16.21
Average Vet Preg Check Cost	$4.83	$3.67

Bale Grazing:
Effect on steer performance, carcass measurement, and net return economics following integrated crop and beef cattle grazing

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Research Brief

Integrated systems research has been evaluated in two separate investigations by Senturklu and co-workers (2018, 2021) comparing crossbred steers that grazed either native range (NR) or annual forages grown on cropland (ANN) before feedlot entry in one study. Following the initial study, a second investigation compared steer groups that had different frame size and evaluated grazing and feedlot performance after delayed feedlot entry. Small framed steers are subject to unfair market bias. Extended grazing and delayed feedlot entry reduced feedlot days on feed 62.4% increased market profitability and eliminated market bias. This study was designed to evaluate the value of bale-grazing as a method to further extend the period of time stocker cattle spend outside of feedlot confinement.

In a three-year follow up study, yearling steers (*n*-144) grazed either an integrated crop-livestock system (ICLS) or a native range control system (NR). After 177.9 days grazing perennial and annual forages (ICLS) or NR only, free-ranging ICLS and NR steers were fed cover crop hay bales 43.6 days to determine transition period bale-grazing effect on finishing performance, carcass measurements, and system net return. The ICLS and NR gains during the 177.9 day grazing period did not differ (ICLS: 1.86 vs. NR: 1.68 lb/d; *P* = 0.24). However, the ICLS 43.6-day bale grazing gain was greater than NR (3.04 vs. 1.77 lb/d; *P* = 0.01). Combined steer grazing growth and bale-grazing growth of 221.5 days, the ICLS treatment group grew at a faster rate (ICLS: 2.10 vs. NR: 1.70 lb/d; *P* = 0.001).

Feedlot arrival weight was greater for ICLS compared to NR (1,255 vs 1,169 lb; *P* = 0.04) and the steers were fed for 95.7 days. Steer ending finished weight did not differ between the two systems (ICLS: 1,582 vs NR: 1,508 lb; *P* = 0.19). Steer gain (*P* = 0.57), ADG (*P* = 0.06), and gain cost (*P* = 0.71) did not differ.

The ICLS steer hot carcass weight (ICLS: 980 vs. NR: 924 lb; *P* = 0.03) and fat depth (ICLS: 0.53 vs. NR: 0.46 in; *P* = 0.04) were greater. NR steer dressing percent (ICLS: 61.83 vs NR: 62.48%; *P* = 0.01) and muscling ratio to HCW (ICLS: 1.50 vs. NR: 1.56 sq. in.; *P* = 0.007) were greater. Choice quality grade was identical for the two grazing methods (98.6 vs. 98.6; P = 1.00).

Combined annual cow and steer winter feed cost were $752.00/steer. ICLS grazing cost for NR was $115.30, pea-barley $74.98, unharvested corn $108.87, and cover crop $58.82 totaling $357.97 compared to $207.77 for the NR system. ICLS and NR steer bale and protein-energy supplement cost was $110.47 vs. 103.05, finishing cost $310.57 vs. 313.67 (*P* = 0.84), and total expense was lower for the NR system ($1531.01 vs. $1376.49). Carcass value was greater for the ICLS steers compared to NR steers ($2013.93 vs. $1921.67; *P* = 0.03). Net returns for ICLS and NR systems were ($482.92 vs. $545.18). The NR system net return was $62.26 greater than ICLS.

These results indicate that the bale-grazing technique is an effective management method for increasing steer weight while withholding heavy stocker cattle from feedlot confinement. As previously shown in other research of Senturklu and others (2018, 2021), reducing the number of days on feed in the feedlot is supportive for greater net return from cattle finishing, which is a high-risk low-profit margin business. Not only does a reduced number of days on feed in the feedlot increase the potential for business profitability, but grazing annual forages grown on cropland in an integrated crop-livestock system contributes to increasing soil organic matter. Soil organic matter feeds the microbial population of soil organisms that are instrumental for soil microbial nutrient cycling. Without question, native range is the gold standard for soil health. Within a cropland environment, adapted crops that have dense root masses coupled with a diverse crop rotation of different root types contribute to an attempt to parallel that of native range. An ICLS system applied to the farm and ranch business where field crops are grown on marginal cropland have the potential to increase net return per unit of acreage with annual forage grazing and delayed marketing off pasture or finishing to final harvest.

An abstract of this research was presented at the 2021 American Society of Animal Science annual meeting, Oklahoma City, OK.

Senturklu, S, **D. G. Landblom**, R. Maddock, T. Petry, C. J. Wachenheim, and S. I. Paisley. 2018. Effect of yearling steer sequence grazing of perennial and annual forages in an integrated crop and livestock system on grazing performance, delayed feedlot entry, finishing performance, carcass measurements, and systems economics. *J. Anim. Sci., Vol. 96(6):2204-2218*.

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The following book chapter abstract was included in the book titled, "Intensive Animal Farming - A Cost-Effective Tactic", published by IntechOpen.

Alternative Intensive Animal Farming Tactics That Minimize Negative Animal Impact and Improve Profitability

Songul Senturklu, Douglas Landblom, Gerald Stokka and Larry Cihacek

Abstract

Animal agricultural businesses strive to improve efficiencies, reduce input costs, and maintain healthy animals with minimal disease control intervention. Bovine respiratory disease is a disease complex that increases when cattle are reared in confinement costing the North American beef cattle industry three-billion dollars or more annually. Principles of soil health define the need to reduce tillage, keep the soil surface covered, rotate crops and plant cover crops for greater plant diversity, maintain living roots in the soil for as long as possible, and integrate livestock grazing into cropping systems. As beef calves age they experience more viral and microbial challenges which stimulate an immune system response resulting in greater disease resilience and well-being when commingled with unfamiliar cattle for confinement feedlot finishing. Wintering calves after weaning in November for modest growth of 0.59 kg/day (1.30 lbs./day) combined with integrated grazing of a sequence of native range and annual forages grown in a diverse multi-crop rotation is a management mechanism that increases calf age (200+ days), promotes structural growth, and delays feedlot entry. Retaining ownership using a vertically integrated business model from birth to slaughter accounting for all business inputs and outputs has resulted in improved environmental balance and business profitability.

Keywords: beef cattle, bovine respiratory disease, sequential grazing, reduced concentrated feeding, integrated crop-livestock system, regenerative agriculture, animal welfare, reduced production cost, net return, profitability

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