Range Fertilization: Plant Response and Water Use

J. ROSS WIGHT AND A.L. BLACK

Abstract

During the 10-year study, herbage production on an unfertilized, mixed prairie range site in eastern Montana averaged 1,047 kg/ha and ranged from 720 to 1,321 kg/ha. Elimination of nitrogen (N) and phosphorus (P) deficiencies by fertilizing increased herbage yields an average of 114% (ranging from a low of 32% in a "dry" year to a high of 218% in a "wet" year). Nitrogen was the major growth-limiting plant nutrient with measurable responses to P occurring only when N was nonlimiting. Single high-rate applications were about equal to annual N applications when compared on an annual rate equivalent basis. Species composition varied as much among years as among fertilizer treatments. At N rates of 336 kg/ha or less, cool-season grasses increased in about the same proportion as did forbs and shrubs, maintaining a relatively constant composition of the major species groups. On unfertilized plots, herbage yields and water use reached maximum values of about 1,250 kg/ha and 265 mm, respectively, regardless of further increases in available water. Unfertilized plots produced an average of 2.60 kg/ha for each 1 mm of precipitation received as compared with 5.81 kg/ha on fertilized plots.

Range fertilization in the northern Great Plains has been researched extensively during the past three decades. Recent reviews of this research clearly established that nitrogen (N) is a major growth-limiting factor in the northern Great Plain (Rogler and Lorenz 1974; Wight 1976). Plant response to phosphorus (P) is much less than to N and occurs primarily as N becomes nonlimiting (Lorenz and Rogler 1972; Wight 1976). Despite the demonstrated limiting effects of N and P deficiencies on plant growth, range fertilization is not a commonly accepted practice because of its cost and its possible long-term ecological effects. This paper reports long-term effects of fertilization on herbage yields and species composition of native range and relates the vegetation responses to climatic conditions.

Methods

The study was conducted on a sandy, glaciated plains range site with a 1 to 2% slope located near Sidney, Mont. Soil was of the Williams series, classified as a member of the fine-loamy, mixed family of Typic Argiborolls. For the past 28 years, annual precipitation averaged 349 mm with 79% occurring during the April-September growing season. Vegetation belongs to the *Bouteloua-Carex-Stipa* (blue grama-threadleaf sedge-needleandthread) faciation of the mixed prairie association (Weaver and Albertson 1956). Basal cover, measured by the point method, was about 13%, half of which was clubmoss (*Selaginella densa*). Western wheatgrass (*Agropyron smithii*), needleandthread (*Stipa comata*), prairie junegrass (*Koeleria cristata*), and threadleaf sedge (*Carex filifolia*) were the major forage species. Goatsbeard (*Tragopogon dubius*) and fringed sagewort (*Artemisia frigida*) were the major forb and shrub respectively.

This paper discusses the results of four separate but similar experiments. Experiment 67A was initiated in 1967 and consisted of factorial combinations of 0 and 45 kg N/ha, and 0 and 20 kg P/ha applied annually through 1976. Treatments were replicated four times on a 6- by 15-m plots. Experiments 69A consisted of single applications of 0, 112, 336, and 1,008 kg N/ha and 0, 112, and 224 kg P/ha applied in factorial combinations in 1969. Treatments were replicated twice on 6- by 6-m plots with P treatments as main plots and N treatments as subplots. Experiment 70A, initiated in 1970, was similar to 69A with the addition of a 672 kg N/ha treatment. Experiment 71A, initiated in 1971, was similar to 69A and 70A except that only two P rates (0 and 224 kg/ha) were used and treatments were applied in a randomized complete block rather than a split-plot design. All fertilizer was applied in early spring using ammonium nitrate and concentrated superphosphate as the N and P sources, respectively.

To provide a common basis for comparison, analysis, and evaluation across experiments, treatments from experiments 69A, 70A, and 71A are also expressed in terms of annual rate equivalents (ARE). The ARE was calculated as total N applied/number of years. For example, the ARE of a single application of 336 kg/ha would be 336, 168, 112, and 42 kg/ha for the first, second, third, and eighth year, respectively, of the experiment. Power and Alessi (1971) and Houlton (1975) showed about equal forage response to equivalent amounts of N whether it was applied in a single application or in several smaller applications over a period of a few years. These results indicated a quantitative carryover of unused fertilizer N.

Herbage yields were determined from one 0.25- by 4.0-m, or one 0.5- by 2.0-m quadrat in each plot, handclipped at ground level. Location of sampling quadrats was changed each year to avoid sampling areas previously clipped to ground level. Yield samples were taken when the major grass species had reached maturity, usually about mid-July. Harvested plants were separated by species, oven-dried at 65°C, and weighed. Species composition was determined on a weight basis. During November each year, all remaining herbage in each plot was harvested to a 10-cm height to prevent litter accumulation.

Soil water content and available soil water were determined for only the unfertilized plots and were estimated from biweekly soil water measurements at a weather station located adjacent to the experimental plots. Measurements were made by the neutron method in three access holes to a 120-cm depth by 30-cm increments. Precipitation was recorded daily at the field-weather station from March to October and at a nearby experiment station the remaining months.

Precipitation-use efficiency was calculated as units of forage produced per unit of precipitation received between harvests. Fall regrowth, which was generally less than 100 kg/ha, was not included in the yield estimates.

Available soil water was calculated as the difference in soil water content at the beginning of the growing season and soil-water content below which water was not available to the plant because it was held at either too high a tension or was positionally unavailable. The minimum level of availability was assumed to be the lowest soil water

Authors are range scientist and soil scientist, respectively, U.S. Dep. Agr., Science and Education Administration, Agricultural Research, Northern Plains Soil and Water Research Center, P.O. Box 1109, Sidney, Montana 59270.

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contents measured during the study period. Plant-available water was calculated as the soil water available at the beginning of the growing season plus precipitation that occurred between the beginning of the growing season and harvest. In this study, April 15 and July 15 were considered the beginning of the growing season and harvest, respectively.

Results and Discussion

Herbage Production

Annual precipitation during the 10-year study period averaged 13% above the long-term (1949-1976) average (Table 1). Of the three below-average precipitation years (1968, 1970, 1971), herbage production on the unfertilized plots was drought restricted only in 1968 and 1971.

Average annual herbage yields of all unfertilized plots are summarized in Table 1. Lowest yields were generally associated with years with lowest precipitation. In 1968 and 1971, the precipitation was only slightly below the long-term average, and the herbage yields were 788 and 720 kg/ha, respectively. Yields were also low in 1973 despite above-average precipitation. This was due in part to untimely distribution of precipitation: during April and May there was a 38-day period when only 7 mm was received. In 1970, a below-average precipitation year, the reverse happened: a high precipitation in April and May plus some carryover soil water from 1969 resulted in yields of the same magnitude as in the above-average precipitation years.

Yields on the unfertilized plots reached maximum values near 1,250 kg/ha and did not increase much beyond this level, regardless of increases in precipitation or plant available water (Table 1). This level of maximum production was reached with as little as 263 mm of plant available water in 1967, whereas 439 mm of plant available water in 1969 did not increase yields above the 1967 level. On this range site, water was a limiting factor only up to the 1,250 kg/ha yield level.

Wight and Black (1971) found that herbage yields from Northern Great Plains rangelands usually averaged less than 1,100 kg/ha and that yield increases due to additional water seldom exceeded 550 kg/ha. Similar results were reported by Smika et al. (1965), where doubling the plant available water by irrigation increased herbage production an average of only 46%. In this study, the maximum yield of about 1,250 kg/ha was only 65% more than the average yield of the three lowest production years (1968, 1971, and 1973). It appears that for the Northern Great Plains, maximum potential yield increases due to above-average annual precipitation are about 50% of the long-term average production rate.

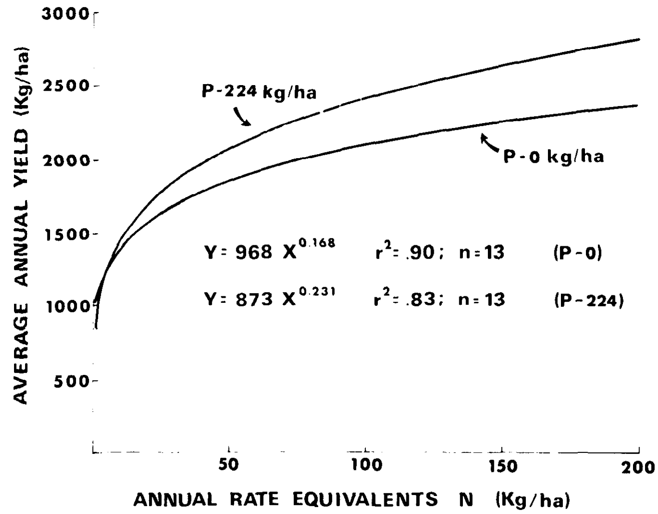

Fig. 1. *The herbage yield–N relationship as affected by P.*

Applications of N and N plus P significantly ($P = 0.1$) increased herbage yields during the 10-year study (Tables 1 and 2 and Fig. 1 and 2). Magnitude of response varied with both the annual climate and application rate. Yield increases due to N plus P applied in nonlimiting quantities ranged from a low of 32% in 1968 to a high of 218% in 1972 with a 10-year average of 114%. This is a little lower than the 143% increase reported by Lorenz and Rogler (1972) working under similar conditions but in a 15% higher precipitation zone.

During the three lowest production years (1968, 1971, and 1973), yield increases due to fertilization averaged 73%. The yields for these 3 years are probably conservative estimates of the long-term average yield for this range site, thus indicating that N and P deficiencies are reducing herbage production by about 550 kg/ha during average production years. During above-average production years, yield decreases due to N and P deficiencies may exceed 2,000 kg/ha.

Most of the yield response to fertilization was due to N (Table 2 and Fig. 1.). Phosphorus increased yields only when applied in combination with N and, when N was nonlimiting, increased yields an additional 20%.

Table 1. Annual harvest-to-harvest precipitation; herbage yields on unfertilized (NF) and fertilized (F) plots; precipitation-use efficiency (PUE); plant available water (PAW), and water use (WU).

	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	Mean
Precipitation (mm)	377	326	527	342	330	493	424	394	368	376	396
Yield[1] (kg/ha)											
NF	1276	788	1245	1205	720	1215	763	933	1321	1100	1057
$S\bar{y} \times t_{.1}$[2]	186	34	112	84	58	84	73	71	92	93	–
F[3]	2323	1041	3538	3466	1529	3866	1332	2008	2535	1608	2325
$S\bar{y} \times t_{.1}$	410	104	434	201	107	240	107	192	172	102	–
F ÷ NF	1.82	1.32	2.84	2.88	2.12	3.18	1.74	2.15	1.92	1.46	2.14
PUE (kg/ha-mm)											
NF	3.38	2.42	2.36	3.52	2.18	2.46	1.80	2.37	3.59	2.93	2.60
F	6.16	3.19	6.71	10.13	4.63	7.84	3.14	5.10	6.89	4.28	5.81
NF											
PAW (mm)	263	199	439	328	212	368	348	309	366	304	314
WU (mm)	227	172	259	265	183	263	245	221	265	228	233

[1]Average from all experiments
[2]The mean plus or minus "$S\bar{y} \times t_{.1}$" is the 90% confidence interval of the mean
[3]Average of plots with N and P nonlimiting from all experiments

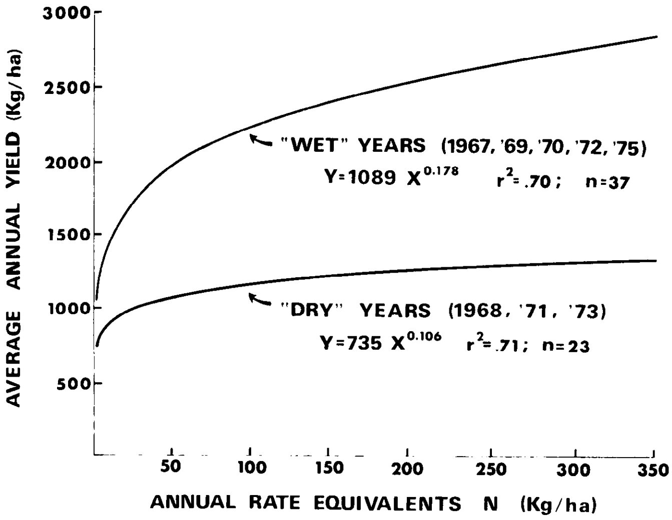

Fig. 2. *The herbage yield–N relationship as affected by climate.*

The relationship between yield and N rate can be expressed bye the equation $Y = AX^b$ where Y is yield (kg/ha) and X is N rate (ARE's) Fig. 1 and 2). Figure 1 shows that most of the yield response to N occurred at the lower rates with only small increases in yield per added increment of N as N rate increased beyond 40 to 50 kg/ha. Economically, the most effective N rates would be in the lower ranges.

Longevity of single, high-rate N applications is shown in Table 2. The 336 and 1,008 kg N/ha rates still had a significant residual effect on yields in 1976, 8 years after application. Power (1972) indicated that N is not likely to be leached through the soil profile in the Northern Great Plains. This is because very little water moves through soil profiles of semiarid rangelands under cover of perennial vegetation as indicated by the soil profile—primarily an accumulation of lime in the upper 1 m of profile. Under conditions where water moves through the profile, fertilizer N losses could be significant.

When yields were averaged over the entire study period, the single, high-rate N applications were slightly more efficient than comparable annual applications. Average annual yields for the annual 45 kg N/ha treatment of experiment 67A and the 42 kg N/ha ARE treatment (single applications of 336 kg N/ha) of experiment 69A were 1,702, and 1,863 kg/ha, respectively. This small difference was due in part to the "N-sink" effect as discussed by Power (1972) and Wight (1976). In experiment 67A, maximum yield responses to annual applications of 45 kg N/ha did not occur until after the fourth year or until a total of 180 kg N/ha had been applied. With single, high-rate N applications, maximum responses occurred the same year as application. Also, the initiation of experiment 69A coincided with 2 years of above-average growing conditions, which allowed for maximum response to the applied N. Because of the sink effect, the most effective N treatments in terms of N use-efficiency may be a high (150 to 250 kg/ha) initial N application followed by annual or periodic ARE applications of 30 to 50 kg/ha. Rates and/or frequencies of N application could be varied in response to climatic conditions.

The initiation of three experiments (69A, 70A, and 71A) in consecutive years, which included both above- and below-average precipitation, provided an opportunity to observe possible treatment-year interactions. In 1971, on plots where N and P were nonlimiting, first-year herbage yields averaged, 1,936 kg/ha in experiment 71A as compared with 1,433 kg/ha in experiments 69A and 70A. In general, there is more response to fertilizer, particularly high rates, the first year of application than in succeeding years because the fertilizer-stimulated root system is able to reach and extract soil water that was not available to the unfertilized roots (Lorenz and Rogler 1967). Also, there was probably a much greater carryover of soil water from the "wet" years of 1969 and 1970 on the previously unfertilized plots of experiment 71A than on the previously

Table 2. Herbage yields (kg/ha) as affected by N and P fertilization (kg/ha) for experiment 69A.

Fertilizer treatment		Year								
N	P	1969	1970	1971	1972	1973	1974	1975	1976	Mean
0	0	1188	1484	797	1205	646	1155	1270	1012	1095
0	112	1250	1069	757	1152	665	952	1437	953	1029
0	224	1254	1096	758	1252	766	1242	1512	1225	1138
Mean		1231	1216	771	1203	692	1116	1406	1063	1087
112	0	2536	1876	1050	1501	1104	1621	1563	1282	1566
112	112	2999	1508	848	1319	883	1164	1435	1117	1409
112	224	3362	1951	925	1380	823	1200	1361	1003	1500
MEAN		2966	1778	941	1400	936	1328	1453	1134	1492
336	0	3177	2564	1122	2189	1165	1500	1667	1522	1863
336	112	5277	3231	1002	2978	834	1455	2003	1176	2244
336	224	4731	3224	1174	2859	1341	1384	1659	1385	2219
MEAN		4395	3006	1099	2675	1113	1446	1776	1361	2109
1008	0	2328	2945	1276	4108	1171	2075	1902	1643	2181
1008	112	3849	3620	1263	4032	795	1583	2097	1877	2389
1008	224	4194	4514	1727	3716	1562	1910	2386	1457	2683
MEAN		3457	3693	1422	3952	1176	1856	2128	1659	2418
LSD[1]		560	SI[2]	209	539	183	232	252	193	162
LSD		971	551	361	934	317	781	743	334	281
LSD		1416	775	472	886	366	568	618	395	271

[1]LSD's are for the N means, N at same P level, and P at same N level, respectively, with error probability=0.1.
[2]Significant N × P interaction.

fertilized plots of experiments 69A and 70A. In most other respects, the three experiments were very similar throughout the study.

Species Composition

The effects of range fertilization on species composition is a major ecological concern. Although this study contributes some knowledge of range species responses to fertilization, the results are limited in application because of the absence of grazing. Results of experiment 67A (Table 3) showed that species composition varied considerably among years on the unfertilized plots. Total perennial grasses, for example, varied from a low of 33% in 1976 to a high of 71% in 1973. The forbs and/or shrubs varied inversely with the grasses, whereas the sedges remained relatively constant throughout the study. Western wheatgrass and needleandthread accounted for much of the variation in percent grasses; whereas goatsbeard and fringed sage accounted for nearly all of the variation in the percent of forbs and shrubs.

The effect of N on species composition was relatively minor and varied with years. One of the largest N-induced changes in species composition occurred in 1972 and 1973 with a 6-fold increase in percent goatsberd and a corresponding decrease in percent perennial grasses, primarily western wheatgrass and needleandthread.

The effects of single, high-rate N applications and annual N applications of smaller magnitude were generally similar with the single, high-rate N applications increasing the percentage of grasses in some instances and the percentage of forbs and shrubs in others. The major difference between the single, high-rate N applications and the 45 kg N/ha applied annually occurred in 1972, a year of tansy mustard (*Descurainia pinnata*) infestation throughout eastern Montana. On plots that had received single applications of 336 kg/ha N or more plus P, tansy mustard yields ranged from 300 to over 4,000 kg/ha. Without P and regardless of the N rate, tansy mustard was absent or only a minor component of the vegetation complex.

Tansy mustard had a degrading effect on the species composition of the infested plots in subsequent years. In extreme cases of infestation, growth of nearly all perennial grasses was suppressed, resulting in secondary successions beginning with fringed sagewort and weedy annuals. The tansy mustard infestation was limited almost entirely to 1972 and some carryover into 1973. We can only speculate on what interaction grazing may have had on this infestation. The young, fertilized tansy mustard plants may have been sufficiently palatable to encourage heavy grazing, thus reducing their detrimental effects.

In agreement with other range fertilization experiments (Wight 1976), the cool-season species responded most to N fertilization. Blue grama, the major warm-season species of this site, was generally not affected by N rates up to 33 kg/ha but its percent composition was reduced as yields of the other species increased. At N rates above 336 kg/ha, blue grama yields decreased. Sedges responded least to fertilization so they also became a smaller portion of the total as production of other species increased.

Water and Precipitation Use

Plant available water for the April 5 to July 15 growing season, as determined from weather station soil water and precipitation data, ranged from 199 to 439 mm, reflecting variability in annual precipitation amounts and distribution (Table 1). Previous work by Wight and Black (1978) showed that N fertilization had little effect on plant available water but it increased water use by as much as 17%. Water use, which was determined only for the unfertilized plots, did not fluctuate as much as did precipitation and plant-available water but increased linearly with plant-available water to a maximum of about 265 mm (Table 1). Above this level there was little or no further increase in water use, regardless of the amount of water available. In this study, water use (evapotranspiration) during the April 15 to July 15 growing season accounted for 59% of the annual precipitation. Wight and Black (1978) reported a similar percentage of 61%, and they found that with N fertilization 70% of the annual precipitation was used during the growing season.

A lack of linear correlation between the harvest-to-harvest precipitation and herbage yields on unfertilized plots reflects both the importance of precipitation distribution within the year and the upper yield limit of about 1,250 kg/ha, beyond which there were no further yield increases, regardless of the amount of precipitation or plant available water. During periods when annual precipitation is average or less most of the time, the yield limit would be reached only infrequently and correlation between precipitation and yield would probably be increased. In this study, N fertilization effectively removed the nutrient-induced yield limit, allowing water (precipitation) to sustain yields well beyond the 1,250-kg/ha limit. Excluding 1973, an anomalous year, the harvest-to-harvest precipitation accounted for half of the variability in herbage yields on fertilized plots ($r^2 = 0.50$; $n = 9$). By measuring annual precipitation between July 1 and June 30, rather than between July 15 and July 14, the

Table 3. Yearly variation in species composition (%) on unfertilized (N_0) and plots fertilized with 45 kg N/ha annually (N_{45}) for experiment 67A.

	Year and N treatment																							
	1967		1968		1969		1970		1971		1972		1973		1974		1975		1976		Mean			
Species	N_0	N_{45}	N_0	N_{45}	N_0	N_{45}	N_0	N_{45}	N_0	N_{45}	N_0	N_{45}	N_0	N_{45}	N_0	N_{45}	N_0	N_{45}	N_0	N_{45}	N_0	N_{45}	*LSD*[1]	
Western-wheatgrass	17	13	17	15	11	10	14	12	20	14	16	28	27	16	18	18	20	11	10	13	17	15	11	12
Blue grama	5	4	8	8	11	11	10	5	9	6	12	2	15	5	12	5	13	3	8	9	10	6	7	10
Prairie junegrass	7	8	5	13	9	10	7	6	12	12	7	1	11	2	16	6	19	18	8	4	10	8	11	11
Needleandthread	7	9	6	10	8	18	10	19	13	30	9	9	17	9	12	15	8	14	2	13	9	15	9	11
Threadleaf sedge	14	7	21	12	13	9	11	11	17	13	8	7	7	19	11	19	14	10	9	5	12	11	12	13
Goatsbeard	3	3	0	0	7	6	4	11	1	1	6	39	6	32	8	10	3	7	7	14	4	12	9	9
Other forbs	8	10	7	10	12	10	15	3	3	2	21	4	7	5	12	9	14	5	13	3	11	6	10	11
Fringed sage	33	40	29	27	18	24	19	26	16	22	14	8	4	6	3	16	4	27	7	12	15	21	16	17
Total grass	36	35	37	47	40	48	43	43	56	61	46	39	71	33	63	44	62	47	33	44	49	44	20	20
Total sedge	20	13	25	17	22	11	17	17	22	14	10	8	10	22	15	21	17	12	16	13	17	15	14	14
Total forbs	10	13	7	10	18	17	19	14	4	2	28	46	13	39	20	19	17	12	34	23	17	19	17	17
Total shrub	35	40	31	17	20	24	21	26	18	22	16	8	6	6	3	16	4	29	16	20	17	22	17	18

[1] The values in the first and second columns are for comparing means among years at the same N-level and means between N-levels within the same year, respectively ($P=0.1$).

correlation was improved significantly $r^2 = 0.85$; $m = 9$). During some years, a significant portion of the annual precipitation occurred within a few days prior to harvest and was only partially reflected in that year's measured production. For example in 1969 and 1970, 105 and 34 mm of precipitation occurred the last 13 and 3 days, respectively, of the growing season.

On rangelands where precipitation is normally the only source of water, its efficient use is critical for maximizing plant growth. Wight and Black (1978) reported that fertilization not only increased the efficiency with which plants utilized water, but it also made more of the precipitation available for plant use by improving soil water recharge. In this study, precipitation-use efficiency averaged 2.60 and 5.81 kg/ha·mm on unfertilized and fertilized plots, respectively (Table 1).

Results of these experiments indicate that range fertilization can be used effectively to increase herbage production without harmful effects to the vegetation complex.

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