Soil Water Use and Recharge in a Fertilized Mixed Prairie Plant Community

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Highlight: Nitrogen fertilization on a mixed prairie, upland range site increased soil water extraction, overwinter recharge, and water- and precipitation-use efficiency. Overwinter recharge was inversely related to soil water content in the fall.

Water is the major growth-controlling factor in arid and semiarid regions, and its efficient management is essential for obtaining and maintaining maximum herbage production. Optimum use of the water resources can be enhanced by increasing the amount of annual precipitation that becomes available for plant use and the efficiency of water utilization during the growth processes. The productivity and subsequent water-use efficiency (WUE) of grassland ecosystems can be greatly increased by fertilization (Smika et al. 1965; Rogler and Lorenz 1974; and Wight 1976). Research has also shown that nitrogen (N) fertilization increases both root growth (Haase 1958; Lorenz and Rogler 1967; and Goetz 1969) and soil water extraction (Smika et al. 1961; and Wight and Black 1972). Lorenz and Rogler (1967) reported that fertilized range plants increased total water use by extracting water to greater depths than nonfertilized plants. The effect in this case was temporary, because there was no subsequent water recharge of the subsoil. Smika et al. (1965) reported that, under natural soil-water conditions, N fertilizer doubled yield but did not increase the amount of water used during the May to July growing season.

This paper discusses the effects of N-fertilization of rangeland over a 4-year period on water use and soil water recharge.

Methods

The study area was located near Sidney, Mont., on a sandy, glaciated plains range site with a 1 to 2% slope. The soil was a Williams fine-loamy, mixed Typic Argiborolls. During the study period, 1970–1973, annual precipitation averaged 426 mm, 29% above the long-term average, with about 70% received during the April to 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*), blue grama (*Bouteloua gracilis*), and threadleaf sedge (*Carex filifolia*) were the major forage species, and accounted for 18, 10, 8, and 16%, respectively, of total herbage production.

Factorial combinations of ammonium nitrate at rates of 0, 112, 336, and 672 kg N/ha and concentrated superphosphate at rates of 0 and 224 kg P/ha were broadcast on 6- by 6-m plots of native range in the early spring of 1970. No fertilizer was applied in subsequent years, and these fertilizer rates, as referred to in this paper, are expressed in terms of annual rate equivalents (ARE)—i.e., a single application of 112 kg N/ha considered over a 4-year period is a 28 kg N/ha ARE treatment. For the 336 and 672 kg N/ha rates, the ARE is 84 and 168 kg N/ha, respectively. Plots were arranged in a split-plot design with P treatments as main plots and N treatments as subplots. In this study, P had no measurable effect on soil water use or recharge, and the P treatments were averaged together for each level of N.

Herbage yields were determined from one 0.5- by 2-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 of each year. Harvested plants were separated by species, oven-dried at 65°C, and weighed. During November of each year, all herbage in each plot was harvested to a 10-cm height to prevent litter accumulation.

Soil water content was measured in 30-cm increments to a depth of 150 cm by neutron-moderation. Measurements were made as early as possible after spring thaw and about every 2 weeks thereafter, during the April to July growing season. Additional measurements were made periodically during late summer and fall.

We calculated WUE as the units (kg) of forage (oven-dried) produced per unit (mm) of water used, where water used represented the change in soil water between the beginning of the growing season and harvest plus the precipitation that occurred during this same period. Soil water measurement dates for specific events are shown in Table 1. Precipitation-use efficiency (PUE) was calculated as the units (kg) of forage produced per unit (mm) of precipitation received between harvests. Fall regrowth was not included in the yield estimates.

Available soil water was the portion of the total soil water content at the beginning of the growing season that was available for plant use—i.e., it could, with time, be extracted by the native vegetation. The lower limits of available or extractable water were estimated as the lowest soil water contents measured over a 6-year period, including the 4 years of this study. Plant-available water was the total amount of water available for plant use during the growing season and included the available soil water plus the April to July growing season precipitation. Available WUE was calculated as the units (kg) of herbage produced per unit (mm) of plant-available water.

Overwinter recharge was determined for 1970-71 and 1972-73 and was calculated as the difference between the soil water content in the fall and the first soil water reading in the spring (Table 1). Nearly all precipitation occurred as snow during this period. Absence of fall soil

Table 1. Soil water measurement dates.

Event	1970	1971	1972	1973
Early spring	3/31	2/24	4/12	3/2
Start of growing season	3/31	4/7	4/12	3/30
Harvest	7/17	7/19	8/1	7/19
Late fall	11/3	—	11/15	11/12

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Table 2. **Effects of N on average herbage yield, water use, recharge, and soil water characteristics, 1970–1973.**

N treatment (ARE) kg/ha	Herbage yield kg/ha	Plant-available water (mm)	Water used (mm)	WUE kg/ha·mm	Available WUE kg/ha·mm	PUE kg/ha·mm	Overwinter[1] recharge (mm)	Total soil water (mm)/ (150 cm profile)[2]	
								Harvest	Fall
0	993	309	233	4.28	3.16	2.51	–4	268	253
28	1558	317	268	5.91	4.90	4.06	26	225	221
84	2389	319	272	8.62	7.29	6.05	44	205	201
168	2638	318	269	9.40	7.80	6.49	32	216	210
LSD (*P* = 0.1)	315	N.S.	18	1.04	0.85	0.78	28	28	28

[1] Average of 1970–71 and 1972–73.
[2] Average of 1970, 1972, and 1973.

water measurements in 1971 prevented the determination of overwinter recharge for 1971-72.

Results and Discussion

Nitrogen fertilization increased herbage production with no measurable differences between the 84 and 168 kg N/ha ARE treatments (Table 2). In this study, N rates had no measurable effect on species composition in terms of the percentage of grasses, forbs, and shrubs.

Nitrogen fertilization did not affect the amount of water available for plant use during the April to July growing season, but it did increase the amount of water used compared to that of the unfertilized system (Table 2). Roots of N-fertilized grasses extracted more water from the soil profile at all soil depths than did roots of nonfertilized grasses (Fig. 1). Total soil water

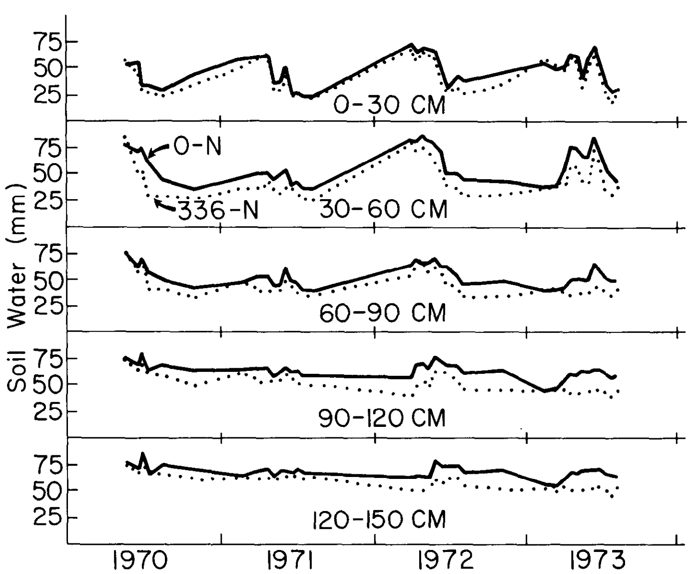

Fig. 1. *Effects of N-fertilization on yearly soil water content.*

content at harvest was 43 to 63 mm less in the fertilized plots than in the check plots (Table 2). However, between harvest in mid-July and the late fall soil measurements, usually in November, the nonfertilized plots lost more soil water than did the fertilized plots. The small amount of water used by the check plots during this harvest-to-fall period prolonged senescence, but was nonproductive in terms of increasing herbage yields. Apparently, semidormant to dormant vegetation continues to extract water from the soil, until limiting soil-water tensions are reached. Even though water loss was higher on the nonfertilized plots than on the fertilized plots between harvest and fall, they retained 32 to 52 mm more soil water in the fall than did the fertilized plots.

During the two periods of measurements (1970-71 and 1972-73), average overwinter soil water recharge was higher on fertilized plots than on the check plots (Tables 2 and 3). Overwinter recharge varied with year and was inversely related ($r = -0.70$; $n = 32$) to soil water content in the fall. This inverse relationship helps explain the lower overwinter recharge on check as compared with the fertilized plots. Similar results have been reported by Black and Power (1965) and Willis and Carlson (1962) in regard to overwinter soil water recharge on summer-fallowed lands.

Variation in annual overwinter recharge is a result of variations in antecedent soil water and winter climate (Table 3).

Table 3. The effect of N-fertilization, antecedent soil water, and winter climate on overwinter recharge.

N treatment (ARE) kg/ha	1970–71 Soil water content-fall (mm)	1970–71 Overwinter recharge (mm)	1972–73 Soil water content-fall (mm)	1972–73 Overwinter recharge (mm)
0	254	27	269	–36
24	221	57	238	–6
84	204	53	194	35
168	221	44	211	20
Overwinter weather characteristics:				
Precipitation (mm)[1]		44	30	
Days of snow cover		93	48	
Average snow depth (mm)		113	88	
Average mean temperature (°C)[2]		–25	–22	

[1] Under windy conditions as prevail in Eastern Montana, snow caught by a gage may be as little as 50% of that reaching the ground surface (Weiss and Wilson 1958).
[2] For December, January, and February.

During the 1970-71 winter, all treatments gained soil water, but the drier, fertilized plots gained the most. However, during the 1972-73 winter, the check and 24 kg N/ha ARE plots lost soil water. This loss could be attributed to higher antecedent soil water in 1972-73 than 1970-71 and the drier, open winter in 1972-73. During 1972-73, snowfall was light and the soil surface was exposed for over half the winter as compared with a nearly continuous snow cover during the 1970-71 winter.

Loss of soil water during the 1972-73 winter indicated that the evaporation process continues throughout the winter and that significant quantities of soil water can be lost when soils of high water content are exposed to the winter air. Loss of water from the 90- to 150-cm profile depth (Fig. 1) was probably due, at least in part, to an upward water-vapor movement along a temperature gradient, intensified by exposure of the soil surface to subzero ambient air temperatures. Other research has also demonstrated that, under the winter climate of the Northern Great Plains, soil water moves upward along temperature gradients and that significant quantities of water can be lost by evaporation from frozen soil surfaces (Willis et al. 1964; and Benz et al. 1968). During the winter of 1972-73, 36 mm of water were lost from the check plots, while the N-fertilized plots had a net gain of as much as 35 mm. With a WUE of 7.29 (Table 2) for the 84 kg/ha ARE N rate, this soil water recharge differential of 71 mm could account for as much as 516 kg/ha forage production the following year (71 m × 7.29 kg/ha·mm). Thus, N fertilization enables range plants to use water that is often lost in winter evaporation.

As indicated in Figure 1, most of the soil water extraction and recharge took place in the upper 60 cm of soil profile. Differences between fertilized and nonfertilized plots at the 90- to 150-cm depth indicated that N stimulates root production in the lower, as well as in the upper, segments of the soil profile. Black (1968), working on a similar site, reported that on unfertilized plots, soil water was not depleted below the 60-cm depth; with N fertilization, soil water depletion extended below the 90-cm depth. As indicated in Figure 1, there was a gradual reduction in subsoil water content of fertilized plots during the first 2 years of study. Lorenz and Rogler (1967) noted similar results in their studies, and they suggested that this additional source of water helped account for some of the initial response of native vegetation to fertilizer. In this study, there was some replenishment of the subsoil water in the fertilized plots during 1972, but replenishment was not sufficient to reach pretreament levels. The fertilized and nonfertilized plots at the greater depths will probably differ in soil water content until precipitation becomes adequate to completely recharge the soil profile. The probability of this happening on semiarid rangelands is low because precipitation is usually limited, and potential water use by perennial vegetation is relatively high (Smika et al. 1965).

Nitrogen fertilization increased the efficiency with which plants utilized water, as indicated by the increases in WUE shown in Table 2. Where N was not limiting during any portion of the study, as in the 84 and 168 kg N/ha ARE treatments, WUE was about double that of the N-deficient checks, increasing from about 4 to over 8 kg/ha·mm. Smika et al. (1965), working with higher levels of available water, reported even greater increases in WUE with applications of N fertilizer. More important, perhaps, is the effect of N fertilization on PUE. This term provides a means of comparing management treatments as to their ability to make use of yearly precipitation taking into account both the effects of fall precipitation on fall tiller initiation, and on forage production the following year, as well as effects of fall and winter precipitation on soil water recharge. On a long-term basis, precipitation is the only water resource available on most rangelands. As seen in Table 2, PUE increased from 2.5 kg/ha·mm for the check to more than 6.0 kg/ha·mm when N was not limiting. Nitrogen fertilization also increased the percent of precipitation that was utilized to grow the crop. Of the total precipitation received between July harvests, 61 and 70% was evapotranspired on the check and fertilized plots, respectively, during the April to July growing season.

The results of this study indicated that N fertilization on a mixed upland range site increases the amount of water that became available for plant use by increasing both soil water use efficiency (WUE) and precipitation use efficiency (PUE). Fertilized vegetation extracted more soil water than nonfertilized vegetation, increasing the overwinter soil water recharge efficiency and providing a larger storage reservoir whenever precipitation was adequate to recharge the soil profile.

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