Energy Fixation and Precipitation-Use Efficiency in a Fertilized Rangeland Ecosystem of the Northern Great Plains[1]

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Highlight

Results of a 2-year study conducted on the mixed prairie near Sidney, Montana, indicated that high rates of nitrogen (N) fertilization accompanied by phosphorus (P) were necessary to obtain maximum levels of energy fixation. Total energy fixed over a 2-year period (1969–70) by the above-ground portion of native vegetation was 1136 kcal/m^2 or 2384 lb./acre yield equivalent. Single applications of 100, 300, and 900 lb./acre of N increased the level of energy fixation 1.6-, 2.2-, and 2.0-fold, respectively, when applied without P; 1.7-, 3.2-, and 2.8-fold, respectively, when applied with 100 lb. P/acre; and 2.0-, 3.0-, and 3.3-fold, respectively, when applied with 200 lb. P/acre. The high N-P treatment decreased the grass plus sedge portion of total yield from 77 to 70% in 1969, but increased it from 61 to 98% in 1970. Increased growth of individual plants and changes in species composition accounted for the high levels of energy fixation by the fertilized vegetation. Precipitation-use efficiency for the 1970 growing season was 110 lb./acre/inch on the unfertilized plots and 336 lb./acre/inch on the high N-P treatment plots.

Life within an ecosystem is dependent upon the ability of chlorophyll-bearing plants within the system to capture or fix energy received from the sun. While the portion of the sun's energy that is fixed is very small, levels of fixation within an ecosystem vary widely in response to environmental conditions. Energy flow in an ecosystem is controlled by man to the extent that he can control the environmental factors related to plant growth or energy fixation. Nutrient availability is one such factor that can be manipulated by man.

Availability of soil water has generally been considered the major growth-limiting environmental parameter on semiarid rangelands. Decreasing yields from the tall grass regions to the short grass regions coincide with decreasing seasonal precipitation. Low yield responses to numerous low-rate fertilization trials on semiarid rangelands have strengthened this concept.

Recently, however, significant yield responses have been obtained from high rates of nitrogen (N) and phosphorus (P) fertilization, indicating that plant nutrients play a major role in energy-fixing processes in rangeland ecosystems of the northern Great Plains.

In Canada, Smoliak (1965), Lutwick et al. (1965), Johnston et al. (1968), and Smith et al. (1968) found that yields increased 2- to 4-fold with applications of 300 or more lb. N/acre. Applications of P with N were beneficial, in most cases, when compared with the effect of the same rate of N applied alone. Johnston et al. (1967) reported yield increases of up to 900% with high rates of N-P fertilizer applications.

In central Montana, high N and P fertilization rates increased yields 3- to 4-fold (Choriki et al., 1969). These workers also reported a 6-fold increase in beef production (24 vs. 150 lb. beef per acre on the check and fertilized pastures) the first year following applications of 300 lb. N/acre and 100 lb. P/acre.

At Mandan, North Dakota, Power and Alessi (1971) compared a single application of 480 lb. N/acre over a 6-year period with three annual applications of 160 lb. N/acre and six annual applications of 80 lb. N/acre and found all three methods of N fertilization were equally effective. Yield increases over the unfertilized plots for the 6-year period were between 3- and 4-fold. Smika et al. (1965) reported a 5-fold yield increase over a 4-year period for native range near Mandan receiving annual applications of 160 lb. N/acre. Rogler and Lorenz (1957), also at Mandan, reported a 3-fold increase in yield over a 6-year period with annual applications of 90 lb. N/acre.

Because fertilizer N and P are immobilized by the soil-plant system, low application rates of N and P fail to supply these nutrients in amounts adequate to meet plant needs. Power (1970 and 1972) estimates that as much as 300 lb./acre N can be immobilized by the biomass of grass roots, mulch, and microbial cells. Thus, nutrient availability has not been fully recognized as a growth-limiting factor in semiarid rangelands.

A study was initiated in 1969 to assess the significance on N and P in the energy-fixing processes of a rangeland ecosystem in the northern Great Plains.

Methods

The study area was located near Sidney, Montana, on a sandy glaciated plains range site with 1 to 2% slope. Annual precipitation averages 13 inches with about 70% received during the growing season (April through September). 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 approximately 13%. Clubmoss (*Selaginella densa*) accounted for 42% of the basal cover, with grasses, sedges (*Carex* spp.), and forbs and shrubs accounting for 24, 15, and 19%, respectively.

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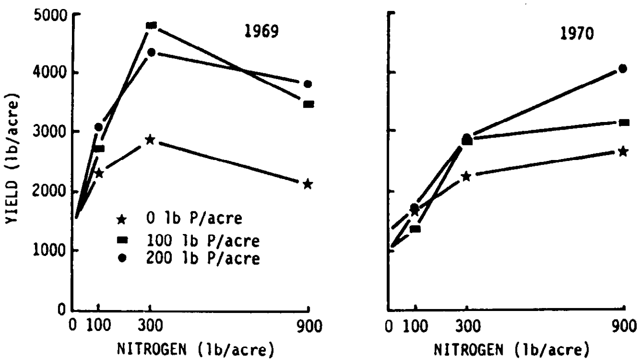

FIG. 1. Effects of N and P fertilization on total yield in a rangeland ecosystem, 1969 and 1970.

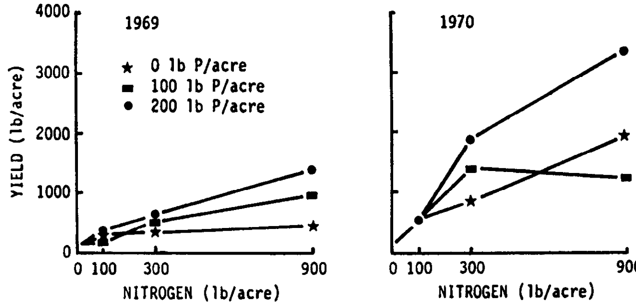

FIG. 2. Effects of N and P fertilization on yield of western wheatgrass in a rangeland ecosystem, 1969 and 1970.

Factorial combinations of ammonium nitrate at rates of 0, 100, 300, and 900 lb. N/acre and concentrated superphosphate at rates of 0, 100, and 200 lb. P/acre were broadcast on 20- by 20-ft plots of native range in the early spring of 1969. Plots were arranged in a split-plot design, with P treatments as main plots and N treatments as subplots. Main plots were randomized within each of two blocks.

Forage yields were determined from one 0.25- by 4-m (9.8- by 157.5-inch) quadrat in each plot hand clipped at ground level. Yield samples were taken when the major grass species had reached maturity. Harvested plants were separated by species, ovendried at 65 C, and weighed. During the spring of 1970, density of western wheatgrass (*Agropyron smithii*) was determined by counting number of culms within a 1.0-ft^2 area in each plot. Forage in all plots was harvested to a 4-inch height during November 1969 to remove part of the old residue.

Soil moisture profiles were determined periodically in the check plots and high fertility plots (900 lb. N/acre and 200 lb. P/acre) by the neutron method.

Precipitation—use efficiency was calculated as the units of forage (ovendry) produced per unit of precipitation received and was based on the plant growth and precipitation that occurred between beginning of harvests in 1969 and 1970. Fall regrowth was not measured. Calculated in this manner, precipitation—use efficiency takes into account both the effects of fall precipitation on fall tillering and on forage yields the following year, and the effects of fall and winter precipitation on soil water recharge. The precipitation—use efficiency term provides a means of comparing cropping or management systems as to their ability to make efficient use of yearly precipitation.

Solar energy was measured with a Moll-Gorczynski type solarimeter located about 1.2 miles from the research area. Net radiation was measured during 1969 with a net radiometer (Fritschen, 1965) placed about 47 inches above the vegetation canopy. Yields were converted to energy fixation based on a conversion factor of 4.25 kcal/g of ovendry plant material (Lieth, 1968; and Morowitz, 1968).

Results

Favorable growing conditions prevailed during most of the 1969 and 1970 growing seasons. Except for April and May of 1969, precipitation was near or above average (Table 1). A heavy snow cover delayed the beginning of the 1970 growing season until April 25.

Energy fixation (yield) in the rangeland ecosystem in which this study was conducted was increased severalfold as a result of N and N plus P fertilization (Fig. 1). In 1969, total yield increased progressively ($P = .10$) with the 100- and 300-lb./acre rate of N, but no additional increase was obtained at the 900-lb./acre rate of N. In 1970, yield increases were progressive with increasing N rates up to 300 lb./acre without P or with 100 lb./acre of P added, and up to 900 lb./acre with 200 lb./acre of P added. This 1970 yield increase was due almost entirely to the increased production of western wheatgrass on the high N-P plots (Fig. 2). Decrease in total production in 1969 at the high N rate was due primarily to decreases in sedges, forbs, and fringed sagewort (*Artemisia frigida*).

The significance of P in the energy-fixing processes of the rangeland ecosystem is demonstrated in Figure 1. Phosphorus applied without N had no effect on yields. However, phosphorus significantly increased total production at the 100-, 300-, and 900-lb./acre levels of N during 1969 but only at the 300- and 900-lb./acre level of N during 1970.

Western wheatgrass was the major component of

Table 1. Seasonal (growth initiation to harvest) climatic characteristics for 1969 and 1970, Sidney, Montana.

Climatic characteristic	20-year average	1969	1970
Start of season (date)	—*	4/4	4/25
Harvest (date)	—	7/16	7/13
Length of season (days)	—	104	80
Seasonal precipitation (inches)	—	13.32	7.70
Monthly precipitation (inches)			
April	1.10	1.53	2.61
May	1.85	0.85	3.38
June	2.87	6.73	2.70
July	1.97	4.70	2.92
Seasonal solar radiation ($kcal/m^{-2} \times 10^5$)	—	4.67	4.03
Seasonal net radiation ($kcal/m^{-2} \times 10^5$)	—	2.36	—

* Data not available.

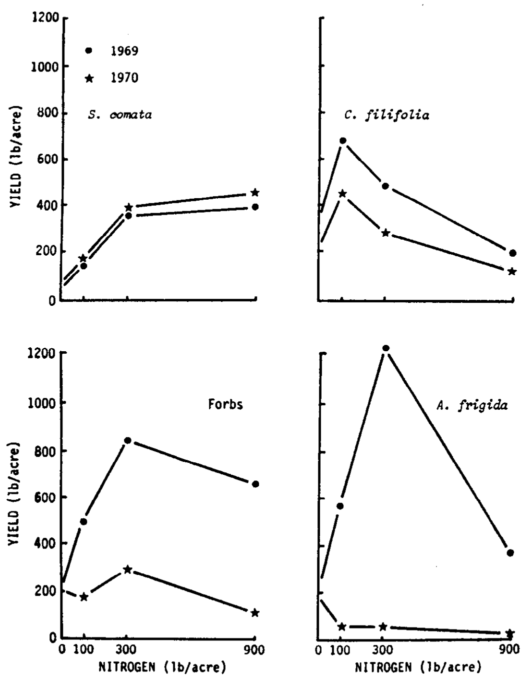

FIG. 3. Effects of N fertilization on yield in a rangeland ecosystem, 1969 and 1970.

vegetation on the N-fertilized plots (Fig. 2). It was the only species that responded significantly to each additional increment of N. This relationship held true in all cases, only at the 200-lb./acre P level. The decrease in western wheatgrass in 1970 on the 900 lb./acre N and 100 lb./acre P treatment was apparently a result of natural variation in the composition of the vegetation on one of the plots. Because western wheatgrass responded to each additional rate of N at the highest P rate, and at each additional rate of P at the highest N rate, it was not determined what N-P rates were necessary for maximum yield.

High rates of N and P fertilization greatly increased density of western wheatgrass culms. In the spring of 1970, culms averaged about 30/ft^2 on unfertilized plots and about 115/ft^2 on plots receiving 200 lb./acre P and 900 lb./acre N. An increase in plant density is the main reason for the increase in yield in 1970 compared to 1969. Additions of N and P also increased number of seed stalks and seed set.

Responses of other major members of the plant community to N fertilization are shown in Figure 3. Because the P effects were not significant (P = .10) for the species in Figure 3, the three levels of P are averaged for each level of N. Forbs and fringed sagewort were stimulated the first year following application of N at rates of 100 and 300 lb./acre but were depressed by the 900-lb./acre rate. Of particular interest is the significant reduction of fringed sagewort at all rates of N the second year following fertilizer application. Threadleaf sedge (*Carex filifolia*) responded only to the 100 lb./acre rate of N. Needleandthread (*Stipa comata*) appeared to reach its maximum production at the 300 lb./acre rate of N. Blue grama (*Bouteloua gracilis*) and prairie junegrass (*Koeleria cristata*), minor yield components of the plant community, were not affected by the fertilization treatments. Another important change in the plant community was the reduction of clubmoss obtained with high rates of N and P. Generally, rates of 300 lb. N/acre and above, with or without P, reduced or eliminated the clubmoss population.

Precipitation-use efficiency in the rangeland ecosystem was greatly improved by additions of N and P. Precipitation between the 1969 and 1970 harvests totaled 12.0 inches. During this period, the unfertilized plots produced 1324 lb./acre of aboveground plant material or 110 lb./acre/inch of precipitation, while plots receiving 900 lb. N/acre and 200 lb. P/acre produced 4026 lb./acre or 336 lb./acre/inch. Fertilized plots were drier than unfertilized plots at the end of the 1969 growing season and remained drier during fall and winter. In December, the high fertility plots contained 5.3 inches water in the top 4 feet of profile as compared to 6.3 inches water for the unfertilized plots. However, snowmelt and April and May precipitation recharged both profiles to about the same level (9.4 inches water/4 feet of profile). The fertilized plots lost water more rapidly than unfertilized plots during the grand growth period of the dominant vegetation. In early July, there were 6.2 inches water in the profile of the high fertility plots and 8.8 inches water in the nonfertilized plots. By harvest and continuing into winter, high fertility plots contained less soil water than unfertilized plots.

Whenever precipitation is adequate to fully recharge the soil profile, fertilized vegetation will likely have more water available for plant growth than unfertilized. The stimulated root systems of fertilized vegetation are able to extract more water from the soil profile than the root systems of unfertilized vegetation. Thus, the fertilized vegetation is, in effect, drawing water from a larger reservoir than the unfertilized vegetation. However, if precipitation is not adequate to recharge the soil profile, then available soil water content will be about the same on both fertilized and unfertilized plots. There was some evidence that plots which were driest in the fall took water in most readily in early spring. Similar results were reported by Black and Power (1965).

Discussion

Results of this study generally agree with similar studies conducted in the northern Great Plains. Yield increases of 3-fold or more, increases in *Agropyron* species, and decreases in clubmoss—all re-

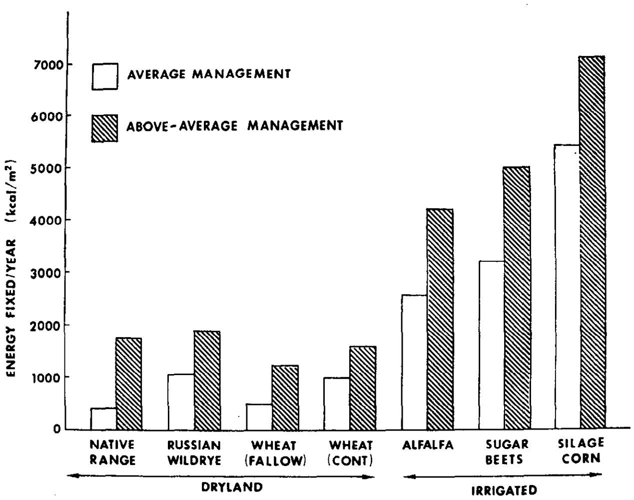

FIG. 4. Energy fixation by various cropping systems near Sidney, Montana, for two levels of management. (Above average for native range represents the annual yield averaged over a 2-year period following a single application of 900 lb N/acre and 200 lb P/acre.)

sulting from high rates of N and P fertilization—are common to this and other work reported. However, Johnston et al. (1967) and Smith et al. (1968) reported increases in shrubs and forbs, whereas in this study, the shrubs and forbs were reduced by N and P applications the second year following treatment.

Energy-fixing capacity of the rangeland ecosystem was compared to that of other crops in the Sidney, Montana, area. Total energy fixed (Fig. 4) was based on average crop yields (G. P. Hartman, *personal communication*) for two levels of management. With the exception of sugarbeets, values in Figure 4 were computed on the basis of aboveground plant production. Values for wheat would be reduced approximately three-fifths if only the grain were considered. In comparing native range to other crops, it should be kept in mind that less than half of the grasses and sedges are harvested under normal grazing conditions and that shrubs and many forbs are utilized very little. Thus, under pristine conditions, native range ranks considerably below the other crops in its ability to capture the sun's energy for use by man. However, when N and P are adequate, native range becomes much more competitive.

Despite wide variation in their energy-fixing capabilities, the crops (Fig. 4) fix only a very small portion of the total yearly solar radiation (less than 0.7% for silage corn). Levels of energy fixation attained by silage corn under irrigation may be near maximum for the Sidney area and indicate that radiation (solar energy) and CO_2 availability should not limit energy fixation in the rangeland ecosystem. Thus, it appears that at least three factors play dominant roles in regulating energy-fixing capabilities of rangeland ecosystems in this area: (1) Soil water availability, (2) genetic potential of chlorophyll-bearing plants in the ecosystem, and (3) nutrient availability.

Results of this study strongly suggest that water—as an immediate requirement for plant growth—does not limit production on rangeland ecosystems to the extent that nutrient availability does. The energy-fixing capacity of the rangeland ecosystem studied ranges from about 250 in dry years to 700 kcal/m^2 in wet years. As indicated in Figure 4, however, the addition of N and P increased the yearly average energy fixation from 568 to 1842 kcal/m^2 during 1969 and 1970. Plant nutrients alone nearly tripled the energy-fixing capacity.

The dominant role of soil water in the energy-fixing processes of a semiarid rangeland ecosystem should not be underrated. In addition to supplying water for transpiration and metabolic processes of plants, soil water is also indirectly related to energy-fixing processes through its effect on genetic potential and nutrient cycling. Genetic potential of a native plant community is primarily a function of species present. These species are, in turn, the product of climatic regimes—primarily temperature and water. Perhaps the most limiting role of water in energy-fixing processes of a rangeland ecosystem is its effect on nutrient cycling. Once an ecosystem has been primed with necessary plant nutrients, and maximum levels of production consistent with existing climatic conditions have been obtained, the ecosystem should continue to function at this new, high energy level with only small additions of nutrients to replace those removed by grazing animals, leaching, and other miscellaneous losses—providing that nutrients cycle fast enough to supply yearly plant needs.

Using nitrogen as an example, some estimates can be made on N requirements and N cycling in the northern Great Plains. Power and Alessi (1971) have reported root weights of 25,000 lb./acre on unfertilized native range near Mandan, North Dakota. Similar values have been reported by Lorenz and Rogler (1967) and Goetz (1969). According to Power (J. F. Power, *personal communication*), increased root growth due to fertilization is about the same amount as increased top growth; and the yearly turnover rate for roots is about one-fourth their total weight. Power also found that N content of roots averages about 0.7% on unfertilized range to about 1.2% on fertilized range. Based upon yields and N content of the aboveground plant material from the experiment reported in this paper, and root yields and N content data of Power, the calculated yearly N requirement on unfertilized range is about 59 lb./acre—N requirement of roots = 44 lb./acre $(25{,}000 \div 4 \times 0.007)$

and N requirement of tops = 15 lb./acre (1192 × 0.013). On fertilized range (high rates of N and P), the N requirement is 165 lb./acre—N requirement of roots = 87 lb./acre [(25,000 + 3,892) ÷ 4 × 0.012] and N requirement of tops = 78 lb./acre (3,892 × 0.02). Assuming a production level equivalent to that of the fertilized range but with no increase in N content of the roots and tops, the N requirement would be 101 lb./acre—[(25,000 + 3,892) ÷ 4 × 0.007 + (3,892 × 0.013)].

As evidenced in this study, nutrient cycling in the northern Great Plains rangeland ecosystems (unfertilized) is inadequate to supply the N necessary for maximum production. These rangelands appear to be cycling N at a rate of 59 lb./acre per year or less (usually less), whereas 101 to 165 lb./acre per year would be needed for maximum yield. The rate at which the N-enriched grassland ecosystem will cycle N is not known. Low soil temperatures in spring, fall, and winter, coupled with long periods of drought in the summer, leave little time for decomposition and nitrification. However, Smoliak (1965) reported from a study in central Alberta that plots receiving an initial application of 300 lb. N/acre were producing 1.6 times more than the check plot after 8 years, indicating an increase in the cycling rate of N as a result of N fertilization. Power (1968) reported that incubation of unfertilized grass roots with soil resulted in a net immobilization of inorganic N, while incubation of fertilized grass roots with soil resulted in a net mineralization of N.

From the results of this experiment and other work referred to, it is evident that plant nutrients—particularly N and P—play a vital role in the energy-fixing processes of rangeland ecosystems in the northern Great Plains. The ecosystems appear to be functioning at an energy level about one-third to one-half that obtainable when N and P availability is adequate. Nutrient cycling, which is directly influenced by the climate—primarily temperature and water—appears inadequate to supply nutrients at rates needed to maintain levels of production consistent with climatic conditions.

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