# CHAPTER 10

# Fertilization of forage crops and rangeland

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## ABSTRACT

The importance of rangeland and tame hay compared to wheat production across the prairies is in part reflected in the area devoted to each, namely, 30.6, 2.9, and 12.8 million hectares, respectively. In the future, we will undoubtedly see an increase of forages grown in rotation where moisture permits. This chapter summarizes N, P, K, S, and micronutrient research findings for both range and tame hay production.

*Nitrogen*

In general, nonlegume forage yields follow curvilinear response curves to a maximum at N fertilizer application rates of 150 to 300 kg N $ha^{-1}$. Growing season precipitation markedly influences response; yield increases per unit of fertilizer N are low and much more inconsistent during dry years. There is also a strong varietal interaction. For example, crested wheatgrass responds much more strongly to fertilizer N than Russian wild ryegrass. Current guidelines suggest relatively low rates of N. Improved guidelines should consider yield, quality, precipitation probability, and a range of hay prices and fertilizer costs, bearing in mind livestock management and current livestock prices.

Properly inoculated legumes will fix sufficient $N_2$ for their own use and may transfer some N to grass in a mixed stand. Maximum yield response to N fertilizer of grass/alfalfa mixtures will be lower than a pure grass stand, depending on the balance in the mixture.

Nitrogen fertilizer is rarely applied to native rangeland. However, yield and stocking rates have been increased by over 300%. Additional benefits include a longer grazing season and improved forage palatability.

While forage protein is increased by N fertilization, forages grown under the semiarid conditions of western Canada already have a high protein concentration. Concern for nitrate toxicity due to N application to forages is usually not warranted at normal rates of fertilization.

Broadcast applications of N are recommended for perennial forages, as conventional banding equipment damages the root system and has difficulty penetrating the dry and tough sod. Ammonium nitrate remains the preferred N source as losses by volatilization are 15 to 20% lower than for urea. Economics remains a determining factor.

Nitrogen application to unfrozen soil in early spring is recommended, with late fall a close second choice. The application of N fertilizer to frozen soils is not recommended.


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*Phosphorus*

A well balanced N and P fertilizer program can prove invaluable to forage and animal productivity. Phosphorus responses have been well documented for Grey Luvisolic and irrigated soils. Older stands are most likely to develop a P deficiency. Very little research has been carried out to determine the P fertilizer requirements of grasses or legumes grown for seed. Native rangeland appears to cycle and utilize soil and fertilizer P quite effectively. The $NaHCO_3$ test has proven useful in predicting the P requirements of forages in western Canada.

*Sulphur*

Alfalfa and clover were among the first crops for which S deficiencies were recognized on Grey wooded soils. Large legume hay yield increases have been measured with small applications of S. Grasses require substantially less S, though research is limited on this topic. Soil tests, plant tissue analysis and N/S ratios have all played a role in defining S deficient forage crops.

Ammonium and potassium sulphates are most effective in the year of application. Gypsum and finely divided elemental S are effective slow release fertilizers, and should be applied in the establishment year for maximum effectiveness.

*Potassium*

The general sufficiency of soil K has precluded extensive research of K fertilizer management practices for forages on the prairies. Organic and certain coarse textured Grey Luvisolic soils are chronically K deficient and the economic production of forages on these soils requires additional K. Older stands of alfalfa are most often deficient, which may lead to increased winterkill with time. Although only a small acreage is affected, the necessity and management of K fertilizer for certain soil types requires better understanding.

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## THE PLACE OF RANGELAND AND FORAGES IN PRAIRIE AGRICULTURE

Native rangeland and seeded forage crops play a vital role in western Canadian agriculture. Forages allow diversity in agriculture by providing grazing land and hay for animal production as well as production of processed feeds and forage seed for export. Marginal land which is not well suited to annual crops can often be utilized by growing perennial forages. Forage crops can help protect and restore erodible and saline soils. Atmospheric $N_2$ fixed by alfalfa and clovers can be used by subsequent crops. In rotation with annual crops, forages can help control problem weeds, diseases and insects. Overall, the mixed farm which combines annual crops with forage crops and animal production often benefits from economic and environmental sustainability.

The area of rangeland exceeds the landbase devoted to wheat production in each of the prairie provinces (Table 1). Most of the rangeland is concentrated in the arid Brown soil zone, and along the forest fringe. Tame hay in rotation with annual crops also occupies a significant area. A portion of the alfalfa hay produced is processed into dehydrated pellets and cubes for export, thereby providing an important secondary industry for local areas. Forages grown for seed production offer an alternate source of farm income. Seed from alfalfa, clovers and grasses grown in the prairie provinces has an international reputation for purity and quality.

Forage crops demand long-term management planning to maintain their productivity. In addition to an understanding of grazing techniques and plant growth dynamics, soil fertility management has proven to be crucial to maintaining productivity. This chapter will examine the progress made in fertilization of rangeland and seeded forage.

## NITROGEN FERTILIZATION

### Yield Response

*Established grass for hay:* Available soil N is usually deficient under established stands of grass, due to the constant uptake of N and complete removal of topgrowth as hay. A forage crop with 18% protein will remove 30 kg N ha$^{-1}$ with each tonne of hay produced. In addition, forages are often grown on inherently infertile soil. The yield of pure stands of seeded grass is almost always sharply increased by N fertilizer. In a few cases, maximum forage yield increases have been reported for annual fertilizer rates over 600 kg N ha$^{-1}$ (Ukrainetz et al., 1988; Cairns et al., 1967). Under irrigation, Leyshon (1991) reported a linear increase in bromegrass forage yield to 200 kg N ha$^{-1}$ applied annually. Typically, forage yield increases curvilinearly to a maximum with annual rates of 150 to 300 kg N ha$^{-1}$, as demonstrated at six multiple year trials in Alberta (Figure 1). In another study near Crossfields, Alberta, N was applied annually for 19 years to a bromegrass stand (Harapiak et al., 1992). Although precipitation from April to July varied from 124 to 368 mm and maximum total dry matter yield varied from 3155 to 8882 kg ha$^{-1}$, the N rate for maximum yield only ranged from 214 to 258 kg ha$^{-1}$.

For dryland production of grass on the prairies, precipitation plays a vital role in forage response to fertilizer. Precipitation received from April to June explained 50 to 90 percent of bromegrass yield in northwestern Saskatchewan (Ukrainetz et al., 1988; Ukrainetz and Campbell, 1988). Timeliness of precipitation is also crucial for maximum response to N fertilizer (Harapiak et al., 1992). As for annual crops, N fertilizer responses are larger and more consistent in wetter years. However, large yield increases have been reported even for very dry conditions in the Brown soil zone (Campbell et al., 1986). In addition, N applications may increase grass regrowth so that a second cut of hay can be taken (Mahli et al., 1986; Penney et al., 1990). Furthermore, even small increases of hay yield in very dry years may be valuable, as hay shortages increase prices.

The growth pattern and yield potential of a particular grass species is an important factor to consider when predicting N fertilizer response. Although all grasses may respond to high rates of N, the relatively low yield potential of certain species may prevent economical yield increases (Lutwick and Smith, 1979). Crested wheatgrass, which establishes quickly in the spring, has shown greater response to N fertilizer than Russian

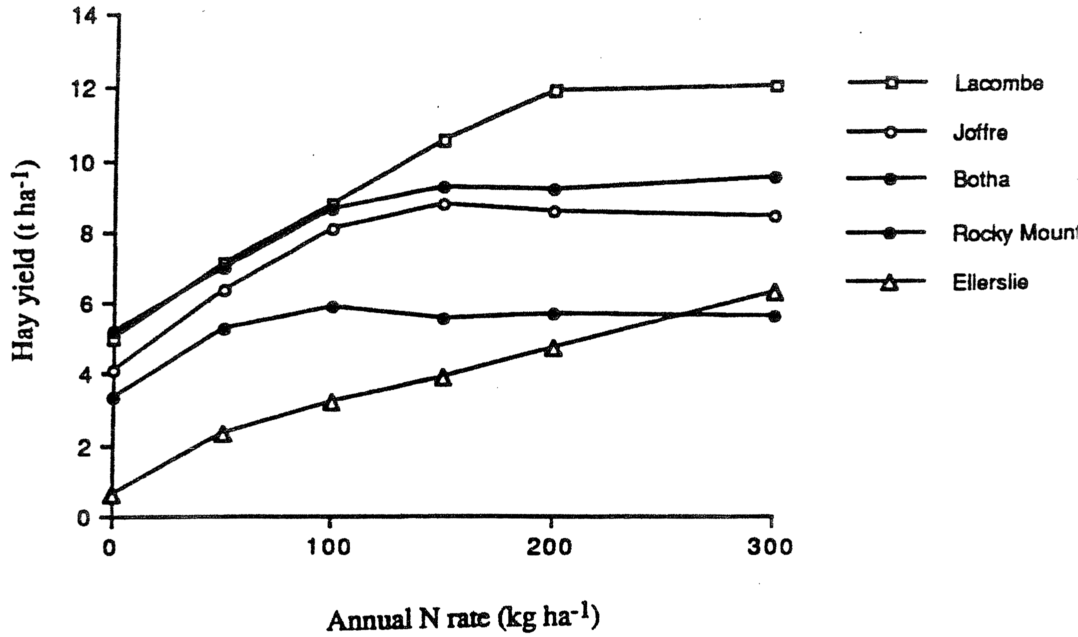


Figure 1. Response of bromegrass hay to N fertilizer at six locations in Alberta (data summarized from Penney et al., 1990; Mahli et al., 1986).

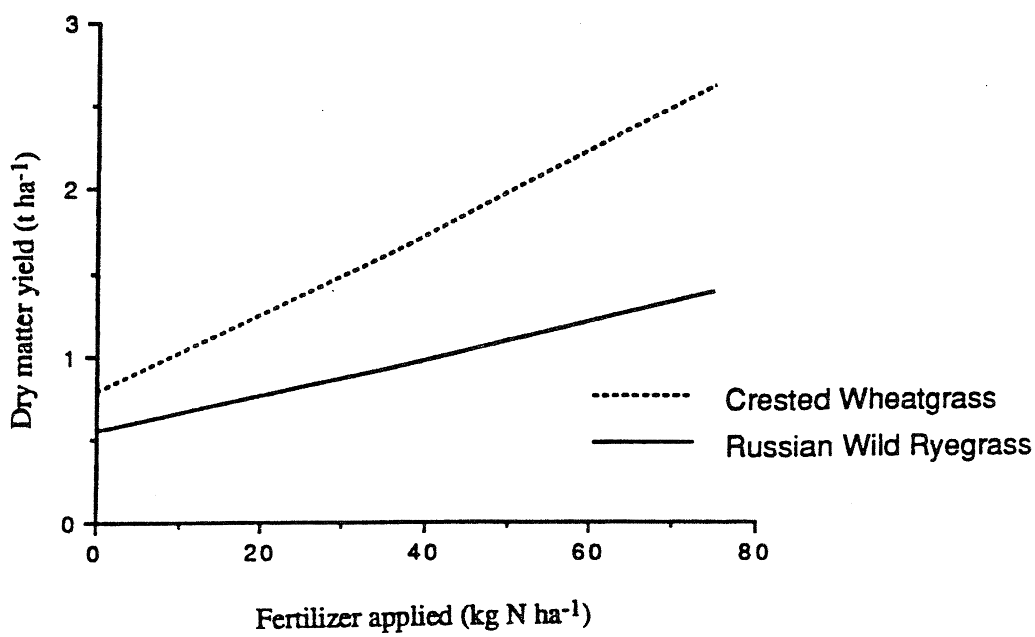


Figure 2. Four year average yield response of crested wheatgrass and Russian wild ryegrass to N fertilizer (from Kilcher, 1958).

wild ryegrass (Fig. 2). Further comparison of grass species N requirements at Swift Current found Altai wild ryegrass to outyield and require more N fertilizer than either Russian wild ryegrass or crested wheatgrass (Lawrence and Knipfel, 1981).

Cold soil conditions limit the growth and fertilizer response of wild ryegrasses (Lawrence and Kilcher, 1972). It appears that Russian wild ryegrass and grasses with similar growth habits are less capable of making efficient use of soil and fertilizer N in early spring, and subsequent immobilization and gaseous loss of N leaves less N for uptake later in the season (Leyshon, 1985). Although extensive fertilizer response comparisons of other grasses were not found in the literature, the vast diversity of species undoubtedly would provide many different yield response equations. For example, reed canary grass, which is best suited to waterlogged conditions, may require N rates well over 400 kg $ha^{-1}$ for maximum yield (Dean and Clark, 1972). Other grasses which require very moist growing conditions such as timothy, fescue and native slough grass might also respond to high levels of N fertilizer.

Economic analyses of optimum N fertilization for seeded grass is difficult, as factors should include hay yield and quality, a range of hay prices, and fertilizer unit and application costs. As available soil N is almost always very low under established grasses, and yields are very sensitive to precipitation, recommendations should preferably be based on soil moisture and precipitation probability. As demonstrated in an economic analysis of fertilization of seeded grass pasture near Swift Current, the market price of the grazing animal is also a useful measure in determining fertilizer profitability (Holt et al., 1991). Current N fertilizer recommendations for Manitoba, Saskatchewan and Alberta generally range from 35 to 130 kg $ha^{-1}$ for established grass, with available soil N and soil or climatic zone determining the required rate (Manitoba Agriculture, 1988; Saskatchewan Agriculture, 1987; Alberta Agriculture, 1981). Optimal N rates for dryland bromegrass stands found in studies in Alberta and Saskatchewan exceed these recommendations (Mahli et al., 1987; Zentner et al., 1989). Under moist growing conditions, the optimal economic

Table 1. Area and production of rangeland and forage crops in Manitoba, Saskatchewan and Alberta compared to area devoted to wheat production.

| | Manitoba | Saskatchewan | Alberta | Prairie provinces |
|---|---|---|---|---|
| Rangeland (ha)[1] | 4 29 000 | 11 532 000 | 14 807 000 | 30 628 000 |
| Tame Hay (ha)[2] | 570 000 | 735 000 | 1 622 000 | 2 944 000 |
| (tonnes)[2] | 2 359 000 | 2 232 000 | 7 117 000 | 11 814 000 |
| Alfalfa pellets (tonnes)[3] | 22 000 | 138 000 | 128 000 | 288 000 |
| Wheat (ha)[2] | 1 815 000 | 8 055 000 | 2 896 000 | 12 766 000 |

1 Area of class 5 and 6 land for agriculture according to the Canada Land Inventory (Environment Canada, 1976)
2 Summarized from Saskatchewan Agriculture and Food, 1989; Alberta Agriculture, 1989; Manitoba Agriculture, 1989 (production data based on 1980-1989 average)
3 From Alberta Agriculture, 1987 (average annual production 1980-1987)

Table 2. A comparison of N fertilizer rates required for maximum yield and optimal economic yield of bromegrass for a four year study at four sites in Alberta (from Mahli et al., 1987).

| Location | Maximum yield | N rate for maximum yield | N rate for optimal economic yield[1] |
|---|---|---|---|
| | ($kg\ ha^{-1}$) | ($kg\ ha^{-1}$) | ($kg\ ha^{-1}$) |
| Lacombe | 12 257 | 278 | 219 |
| Joffre | 9 250 | 213 | 159 |
| Botha | 5 519 | 192 | 69 |
| Rocky Mountain House | 8 013 | 209 | 130 |

1 Optimal economic yield assuming N prices of \$550 $t^{-1}$ and hay prices of \$40 $t^{-1}$

rate of fertilizer may approach the N rate required for maximum yield (Table 2). A similar economic analysis of a Manitoba trial also demonstrated the economic importance of adequate N fertility for several grass species (Table 3). Again, economic conditions often support N fertilization at rates higher than the current recommendations of soil testing laboratories.

*Grass for seed production:* Grass grown for seed production without removal of residue will remove very little N from the soil each year. Long-term N fertilizer requirements should be substantially lower in comparison to hay crops. Unfortunately, few studies have examined this topic.

Trials with Altai wild ryegrass at Swift Current found no relationship between fertilizer N and seed yield; however, there was also little increase in total dry matter yield (Lawrence et al., 1980). Other work has measured increased production of flowering shoots and seed per shoot with adequate N supplies. Maximum seed yield was generally attained with less than 100 kg N $ha^{-1}$, much lower than for total yield (Thompson and Clark, 1989; Ukrainetz, 1974). However, data from a N fertilization trial with bromegrass in northwest Saskatchewan measured a similar trend in hay and seed yield, as both were increased by as much as 300% (Ukrainetz, 1969). Earlier studies in Saskatchewan also described large bromegrass seed yield increases, with response curves similar to total yields (Fig. 3).

*Grass-alfalfa mixtures for hay:* Legumes, including alfalfa and clovers, are capable of fixing atmospheric N when properly inoculated with a suitable *Rhizobium* seed treatment. Nitrogen fertilizer is therefore not required for forage legumes when seeded as a pure stand. The only exception to this rule is during forage establishment. Forage legumes are often seeded with a nonlegume companion crop to provide an interim income and to reduce erosion and weed growth in the establishment year. For this system it is advisable to apply N fertilizer to satisfy the requirements of the nonlegume crop, and P fertilizer to the requirement of the forage crop (Bittman et al., 1991).

Table 3. Economic optimum fertilizer N (kg $ha^{-1}$) for grasses in southwester Manitoba, assuming average spring precipitation (167 mm April-June) (from McCaughey et al., 1990).

| Grass Species | N price | Hay price | | |
|---|---|---|---|---|
| | | 20 | 40 | 60 |
| | ($\$ t^{-1}$) | ($\$ t^{-1}$) | | |
| | *Sandy loam soil* | | | |
| Bromegrass | 400 | 53 | 130 | 156 |
| | 600 | 0 | 92 | 130 |
| Crested wheatgrass | 400 | 0 | 99 | 159 |
| | 600 | 0 | 9 | 99 |
| Russian wild ryegrass | 400 | 0 | 46 | 107 |
| | 600 | 0 | 0 | 46 |
| | *Clay loam soil* | | | |
| Bromegrass | 400 | 65 | 214 | 263 |
| | 600 | 0 | 139 | 214 |
| Crested wheatgrass | 400 | 0 | 218 | 319 |
| | 600 | 0 | 68 | 218 |
| Russian wild ryegrass | 400 | 38 | 175 | 220 |
| | 600 | 0 | 107 | 175 |

Table 4. Dry matter yield and protein concentration of grasses fertilized annually with 50 kg $ha^{-1}$ of N fertilizer at two sites in Saskatchewan (from Campbell et al., 1986).

| Year | Dry matter yield | | Protein concentration | |
|---|---|---|---|---|
| | Check | Fertilized | Check | Fertilized |
| | (kg $ha^{-1}$) | | (%) | |
| | *Swift Current* | | | |
| 1981 | 977 | 1144 | 15.0 | 13.3 |
| 1982 | 1222 | 1955 | 11.4 | 12.3 |
| 1983 | 752 | 1245 | 9.1 | 9.8 |
| 1984 | 195 | 325 | 13.6 | 15.1 |
| | *Scott* | | | |
| 1982 | 664 | 1678 | 7.1 | 12.8 |
| 1983 | 641 | 978 | 11.2 | 13.1 |
| 1984 | 848 | 1922 | 9.6 | 8.4 |

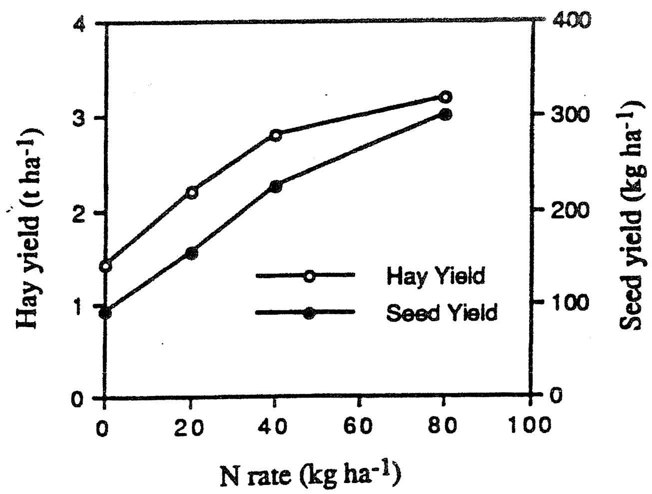


Figure 3. Hay and seed yield response to N fertilizer at five sites near Unity, Saskatchewan (from Knowles and Cooke, 1952).

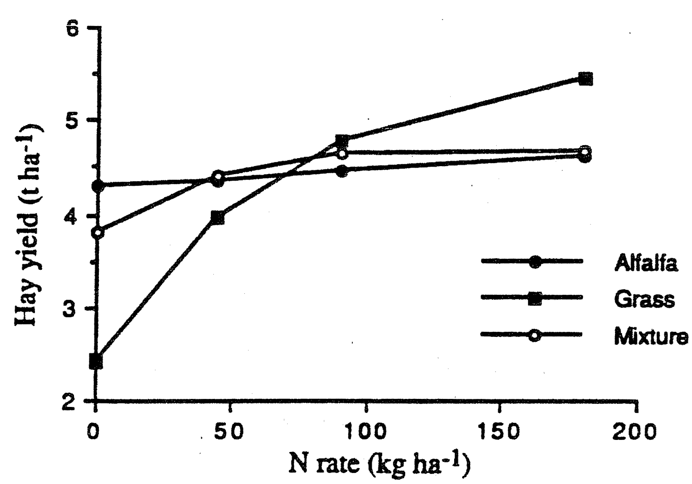


Figure 4. Average yield of alfalfa, crested wheatgrass and alfalfa-grass mixtures as affected by N fertilizer. Alfalfa component of the mixture was 67, 53, 51 and 48% for N rates of 0, 45, 90, and 180 kg $ha^{-1}$, respectively (from Lutwick and Smith, 1977).

Grass grown for forage in western Canada is often seeded in mixtures with legumes, particularly alfalfa. The mixture thus benefits from N fixation from the legume, balanced with roughage provided from the grass. Properly inoculated alfalfa will fix sufficient N for its own use and transfer N to the associated grass (Leyshon, 1985; Fairey, 1991). As a result, N fertilizer requirements for well balanced grass-alfalfa mixtures are much lower than for pure grass stands (Fig. 4). Maximum herbage yields are usually met with 50 to 100 kg N $ha^{-1}$. If higher N fertilizer rates are used, the grass component of the mixture will increase and may crowd the alfalfa out (Fig. 5). If this occurs, N requirements for the forage stand will increase and the forage quality will decrease as the alfalfa is lost. Therefore, the best fertilizer management scheme for forage mixtures is site specific (Nuttall et al., 1991; Holt, 1983; Nuttall et al., 1980). However, at least small N applications are often economical, and may improve the yield of the grass component, its survival and the quality of forage mixtures (Cooke et al., 1968; Holt and Zentner, 1985).

*Native rangeland:* Native prairie and wetlands represent over 90% of the total landbase used for forage production on the prairies, but fertilizer is rarely applied to increase productivity of these areas. Difficult terrain, low yields and only periodic use precludes long-term management of most native areas for forage production. However, research has shown the potential benefit of fertilizer application to forage growth and subsequent animal carrying capacity and range stability. In an early study at seven rangeland sites across the prairies, which normally produced 460 to 1100 kg of dry matter $ha^{-1}$, yield was increased by 330 to 670 kg $ha^{-1}$ with an application of 66 kg N $ha^{-1}$ (Kilcher et al., 1965). Application of varying rates of N fertilizer in southeastern Alberta increased dry matter yields and animal unit stocking rate by as much as 300 to 900%. Additional benefits included a 3 to 5 week longer summer grazing season, increased winter grazing, and improved palatability of the forage in fertilized areas (Johnston et al., 1967, 1968; Smith et al., 1967). There was also sharp changes in native vegetation composition

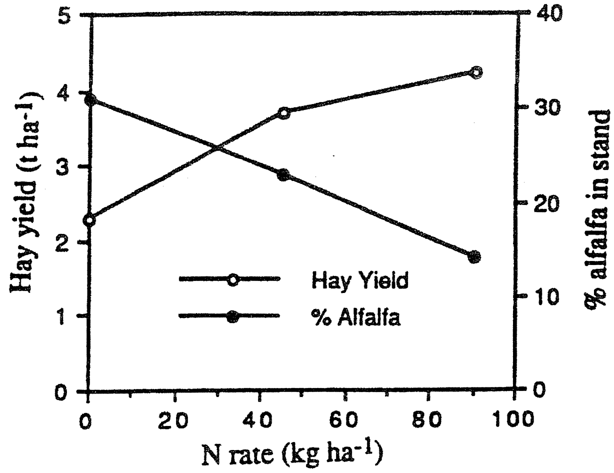


Figure 5. Effect of N application on hay yield and percent alfalfa in a bromegrass and alfalfa stand in the first year after fertilization (from Nuttall et al., 1991).

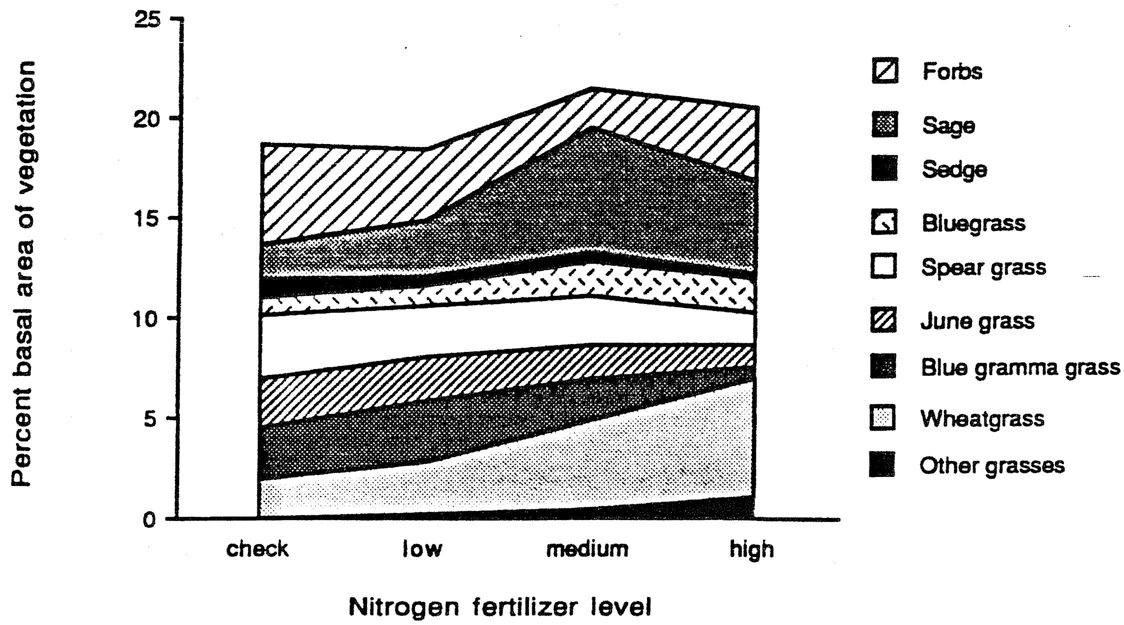


Figure 6. Effect of fertilizer on vegetative composition of native rangeland in southeastern Alberta as affected by increasing rates of N fertilizer (from Johnson et al., 1967).

after fertilization, and thus these authors cautioned that excessive N fertilizer application may increase growth of opportunistic, weedy, and sometimes poisonous species (Fig. 6).

Unfortunately, little information is available to determine the best fertilizer rates for rangeland, and no research has yet examined the potential fertilizer response of native grasses in more humid areas of the prairie. With increased interest in maintaining native areas for soil and wildlife conservation purposes, long term management and research should investigate soil nutrient requirements of these systems.

**Forage Quality Response**

*Protein concentration and palatability:* Protein concentration is the primary criterion used to measure forage quality. Nitrogen is a central component of proteins, and N fertilizer application certainly increases protein concentration of forages (Lawrence et al., 1970; Campbell et al., 1986; Mahli et al., 1986; Ukrainetz and Campbell, 1988; Ukrainetz et al., 1988). However, protein concentration is not increased as quickly nor to the same degree as total yield, and the protein concentration of higher yielding grass species is less affected (Lawrence, 1973; Lawrence et al., 1982; Ukrainetz, 1974; Campbell et al., 1986). Rapid yield increase of grass due to N application may dilute other plant constituents, increasing the need for feed additives (Lawrence et al., 1982). The response pattern of yield and protein to N fertilizer will vary from year to year, with higher protein concentrations more likely to occur in dry years when dry matter yields are low (Table 4). In some cases, rapid growth after N application may in fact dilute protein concentration (Ukrainetz et al., 1988; Penney et al., 1990; Leyshon, 1991). In contrast to yield, there is little difference in protein concentration among species, although higher yielding grasses may require more N to reach maximum protein concentration (Smith and Lutwick, 1975; Campbell et al., 1986).

As forages grown on the arid prairies usually have high protein concentrations, it is rarely practical to apply N fertilizer to increase hay protein. An occasional exception to this rule may be found in the humid Grey soil zone (Toogood, 1972; Nuttall, 1976).

Forage palatability is frequently improved with N fertilization. Several reports describe preferred grazing by livestock of fertilized areas in pasture (Johnston et al., 1967; Smith et al., 1967; Read, 1969; Read and Winkleman, 1982). Digestible cellulose content of hay also increases, rendering the hay more useful for animal growth and weight gain (Toogood, 1972; Ukrainetz, 1974; Lawrence and Knipfel, 1981; Holt et al., 1991). The additional forage produced with N fertilization is also more valuable as a feed source.

*Nitrate concentration:* Nitrate concentration of forage places a constraint on maximum N fertilizer rates. Excessive levels of nitrate in forage may lead to nitrite poisoning, especially of ruminant animals. Acute toxicity levels vary among animal types and feeding methods, but generally the $LD_{50}$ ranges from 160 to 224 ppm (i.e., mg $NO_3$ $kg^{-1}$ animal body weight). Chronic toxicity levels are less well defined (Wright and Davison, 1964). As a rule of thumb, feed should contain no more than 0.5% nitrate (Saskatchewan Agriculture, 1987). Numerous research trials have provided guidelines to avoid toxic nitrate levels in forages as a result of N fertilization.

Fertilizer rates well over 100 kg N $ha^{-1}$ pose no risk (Cairns, 1968; Penney et al., 1990). However, numerous studies report toxic levels of nitrate in hay fertilized with 200 kg $ha^{-1}$ or more N (Lawrence et al., 1968; Ukrainetz, 1982; Ukrainetz and Campbell, 1988; Penney et al., 1990). Repeated annual fertilization at lower rates may also lead to a buildup of residual available soil N and occasional high forage nitrates (Ukrainetz et al., 1988; Leyshon, 1991).

Yearly trends in nitrate accumulation are not consistent from year to year (Fig. 7). Similar to protein, high nitrate levels are associated with dry years and high available soil N contents.

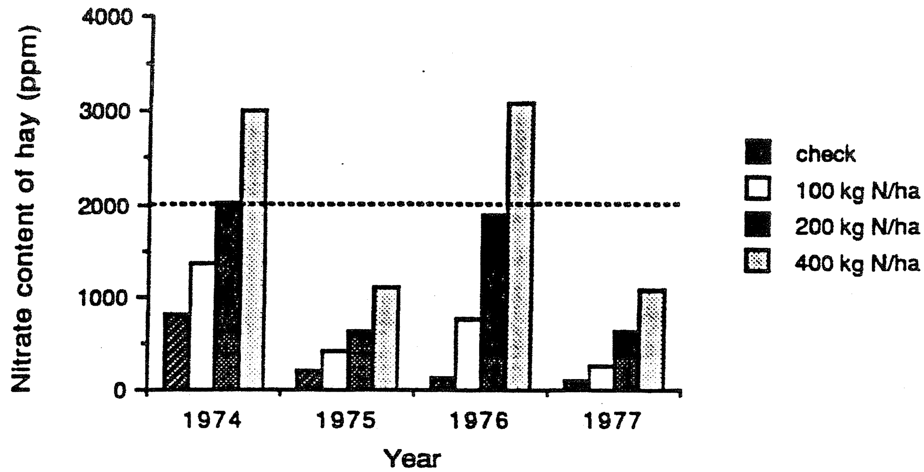


Figure 7. Yearly variation of nitrate in Altai wild ryegrass as affected by annual applications of N fertilizer. The average accepted acute toxic level of nitrates in forage is 2000 ppm (from Lawrence et al., 1980).

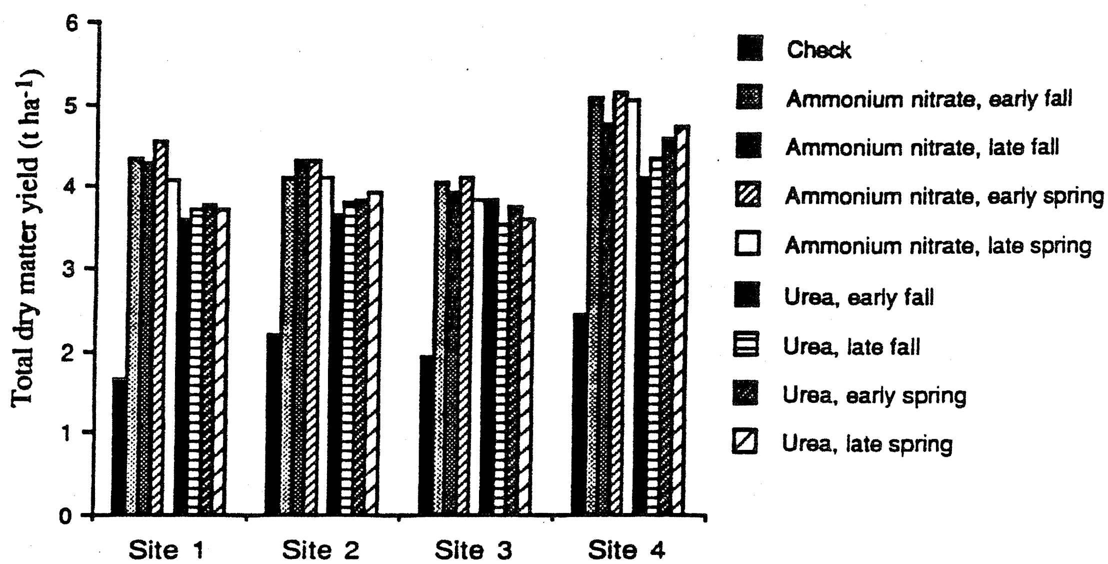


Figure 8. Average yield of bromegrass fertilized annually with ammonium nitrate or urea for 14 years at four sites in Alberta. The application times correspond to: early spring - early to mid April; late spring - mid to late May; early fall - late September; and late fall - late October (from Mahli et al., 1992).

Nitrate accumulation is associated with luxury uptake of N and occurs when the N fertilizer rates exceed that required for maximum yield and therefore maximum economic yield (Smith and Lutwick, 1975; Mahli et al., 1986). For all practical purposes, a rational fertilizer management program will not induce nitrate toxicity in hay. However, frost or physical damage (hail) to a hay crop may cause an accumulation of nitrates in plant tissue.

**Form and Placement of N**

Most fertilizer is usually broadcast on perennial forages, because conventional banding equipment damages the established root system and often has difficulty penetrating the tough sod (Leyshon, 1982). For this reason, ammonium nitrate has traditionally been considered the best N source for forages, as the nitrate component is more easily leached into the soil by precipitation. However, urea and anhydrous ammonia are substantially less expensive than ammonium nitrate, and may prove to be the preferred forms of N fertilizer. In humid areas, broadcast urea may even be as effective as ammonium nitrate (Power, 1974). Only limited research has examined broadcast applications of urea-ammonium nitrate solutions (28-0-0) for forages. Nitrogen solutions applied in this manner appear to be very ineffective (Bailey, 1974).

Numerous trials have compared granular ammonium nitrate to urea as a forage fertilizer for the Canadian prairies. A survey of published data shows the relative advantage of ammonium nitrate in terms of yield response and total N fertilizer recovery for broadcast applications (Table 5). Time and rate of N application, field conditions, seasonal precipitation and grass species all impact on the efficiency of use of urea fertilizer for a specific site, as described by the authors of each study. For most conditions, urea appears to be about 85% as efficient for yield increase and nearly 80% as efficient for fertilizer recovery as compared to ammonium nitrate. The relative cost and availability of each fertilizer source will determine the best choice (Campbell et al., 1986; Zentner et al., 1989).

Table 5. Relative efficiency of urea and ammonium nitrate fertilizer for broadcast application to grass for trials conducted in western Canada.

| Source | Measurement parameter | Relative effect of urea fertilizer |
|---|---|---|
| | | (% of ammonium nitrate) |
| Campbell et al., 1986 | Dry matter yield | 87 |
| | Fertilizer recovery | 70 |
| Cairns, 1968 | Dry matter yield | 92 |
| | Fertilizer recovery | 82 |
| Ukrainetz, 1982 | Fertilizer recovery | 74 |
| Harapiak, 1979 | Dry matter yield | 69 to 80 |
| Harapiak, 1979 | Dry matter yield | 78 to 82 |
| Mahli et al., 1992 | Dry matter yield | 89 |
| | Fertilizer recovery | 75 |
| Penney et al., 1990 | Dry matter yield | 92 |
| | Fertilizer recovery | 85 |
| Campbell et al., 1988 | Dry matter yield | 85 |
| | Fertilizer recovery | 78 |
| Rowell, 1984 | Dry matter yield | 99 |
| Ukrainetz et al., 1985 | Dry matter yield | 88 |
| Ukrainetz et al., 1985 | Dry matter yield | 82 |
| | Fertilizer recovery | 66 |
| Ukrainetz & Campbell, 1988 | Dry matter yield | 87 |
| | Fertilizer recovery | 76 |

Again, the literature surveyed compared only broadcast applications of urea and ammonium nitrate. Very few data are available to evaluate band application of N fertilizer for forages, although in a recent study in Alberta, urea placed in a band produced 15% more dry matter on average than when broadcasted (Mahli and Ukrainetz, 1990).

An alternative to banding urea fertilizer to reduce volatile N losses is to use slow release types of fertilizer. At two sites in Alberta, S-coated urea effectively increased N fertilizer use efficiency in comparison to conventional forms of urea or ammonium nitrate by nearly 80 percent. Other types of slow release urea and urea coated with urease inhibitors were ineffective (Rowell, 1984). In direct contrast, S-coated urea proved much less effective than urea or ammonium nitrate as a fertilizer for grasses in Manitoba (Bailey, 1974).

Little or no research has critically evaluated liquid fertilizers or anhydrous ammonia for forages. As better application equipment becomes available, these N sources may prove their effectiveness. Spoke wheel applicators and high pressure injectors that are currently being developed for liquid fertilizer applications have obvious potential for forage fertilization because they would allow fertilizer application into the soil without root disturbance.

### Timing of N Application to Forages

As observed for annual crops, the relative merit of fall versus spring fertilizer applications have been the focus of many experiments. In addition, annual fertilization of perennial forages has often been compared to single large fertilizer applications repeated once every several years.

Nitrogen fertilizer increases hay yield more when applied to unfrozen soil in early spring than at any other time (Harapiak, 1979a; Campbell et al., 1986; Mahli et al., 1992). Even so, applications in fall produce nearly as large a hay yield response (Fig. 8). The real and opportunity cost of N fertilizer in spring compared to fall is an important a factor in timing fertilizer application. Research in the Brown and Dark Brown soil zones has suggested net returns are highest when N fertilizer is applied in April, despite higher costs, but application of N in October and November sometimes provides an equivalent or higher return (Campbell et al., 1986).

There has been some interest in N fertilization in winter, as a means of spreading out farm workload. However, the poor recovery and dry matter response to fertilizer applied to frozen or snow covered soil prevents this from being a recommended practice (Harapiak, 1979a; Campbell et al., 1986).

The effect of time of N application on forages grown for seed is not as well studied nor understood. Fertilizer applied in early fall or even summer may stimulate seed yield production more than that applied in spring (Knowles and Cooke, 1952). Timing of application may be more crucial for seed crops, and may vary among species.

Power (1967) suggested a fertilizer management scheme for the arid grasslands in which large single applications of N fertilizer would quickly buildup available soil N. The arid prairie climate would prevent any leaching losses of N and, in theory, residual fertilizer would sufficiently supply the grass with N for several years, as moisture became available (Read and Winkleman, 1982). Fewer applications would make long-term planning for grassland much more manageable. In light of this idea, several studies were designed to compare annual and large single applications of N fertilizer in western Canada (Mahli et al., 1986; Campbell et al., 1988; Ukrainetz et al., 1988 ; Penney et al., 1990). It was soon apparent that very high rates of N fertilizer could not be recommended. As previously discussed, toxic levels of nitrate accumulate in forage fertilized beyond the rate required for maximum yield, particularly in early years after application (Ukrainetz et al., 1988). Furthermore, hay yields are larger, more uniform, and of higher quality with an annual N fertilizer management program (Table 6). Annual fertilization has also proven more profitable in terms of beef production on grazed pasture (Holt et al., 1991). Nitrogen

Table 6. Yield and protein concentration of bromegrass fertilized annually for three years or with single applications of comparable amounts of ammonium nitrate (from Penney et al., 1990).

| | | N fertilizer applied | | | | |
|---|---|---|---|---|---|---|
| Location | Year | 0 | Single 150 | Annual 3 x 50 | Single 300 | Annual 3 x 100 |
| | | (kg $ha^{-1}$) | | | | |
| | | *Dry Matter Yield (t $ha^{-1}$)* | | | | |
| Ellerslie | 1 | 0.89 | 4.28 | 2.79 | 4.88 | 3.20 |
| | 2 | 0.26 | 0.53 | 1.36 | 2.33 | 3.01 |
| | 3 | 0.69 | 0.72 | 2.74 | 0.69 | 3.37 |
| Vimy | 1 | 1.73 | 4.76 | 3.15 | 6.64 | 3.95 |
| | 2 | 2.18 | 3.14 | 3.63 | 4.11 | 5.69 |
| | 3 | 2.47 | 3.10 | 4.23 | 2.12 | 5.42 |
| | | *Protein Concentration (%)* | | | | |
| Ellerslie | 1 | 11.9 | 14.8 | 12.0 | 18.4 | 13.9 |
| | 2 | 10.4 | 9.7 | 13.2 | 8.8 | 15.8 |
| | 3 | 7.7 | 8.0 | 7.8 | 9.2 | 10.2 |
| Vimy | 1 | 14.6 | 17.6 | 10.9 | 19.6 | 13.7 |
| | 2 | 10.5 | 8.4 | 9.3 | 8.7 | 10.7 |
| | 3 | 14.1 | 13.0 | 10.5 | 10.4 | 11.3 |

Table 7. Livestock production and carrying capacity of pasture managed under different fertilizer programs (from Mahli et al., 1987).

| Fertilizer program | Animal weight gain | Carrying capacity |
|---|---|---|
| | (kg $ha^{-1}$ $yr^{-1}$) | (steer-$days^{-1}$ $ha^{-1}$ $year^{-1}$) |
| | *Years 1-3* | |
| No fertilizer | 209 | 97 |
| 37 kg N $ha^{-1}$ | 247 | 117 |
| 37 kg N $ha^{-1}$ + 20 kg P $ha^{-1}$ | 283 | 126 |
| | *Years 4-6* | |
| No fertilizer | 170 | 93 |
| 72 kg N $ha^{-1}$ + 40 kg P $ha^{-1}$ | 352 | 148 |
| 144 kg N $ha^{-1}$ + 78 kg P $ha^{-1}$ | 410 | 175 |

fertilizer management requires yearly attention for successful forage production (Lutwick and Smith, 1979).

## PHOSPHORUS FERTILIZATION

### Yield Response

*Established grass for hay:* Phosphorus fertilizer applied alone to seeded grasses has not consistently increased hay yield in western Canada. However, when adequate N fertilizer is also applied, grass yields are often significantly increased by P additions (Fig. 9). This interactive N-P yield response has been well documented in a number of studies (Harapiak, 1979b; Ukrainetz et al., 1988; Nuttall et al., 1991; Ukrainetz and Campbell, 1988). Although P deficiencies are not as universal as N deficiencies for grasses on the prairies, yield increases of well over a tonne of hay per hectare are not uncommon. A well balanced N and P fertilizer program can prove invaluable toward pasture management, because forage and animal productivity are both improved (Table 7).

Unfortunately, the relationships between increasing P rates and grass yields is not well established, nor have the soil and climatic conditions which determine if a P response will occur have been fully documented. Complex biocyling of inorganic and organic P compounds also plays a major role in P nutrition of perennial grasses, and requires a better understanding.

*Alfalfa and clovers for hay:* Alfalfa has a large requirement for P, typically removing 2 to 3 kg $ha^{-1}$ of P per tonne of hay. In spite of this uptake, its response to P fertilizers on the prairies often has been small and insignificant (Nuttall, 1985a; Bittman, 1991; Simons et al., 1991). Alfalfa apparently has a greater ability to utilize soil P than annual crops, thus yield responses to P fertilizer are often not measured in the first years of an alfalfa stand. As the alfalfa continues to draw on available P and top-growth is constantly removed, requirements for added P fertilizer increase (Fig. 10).

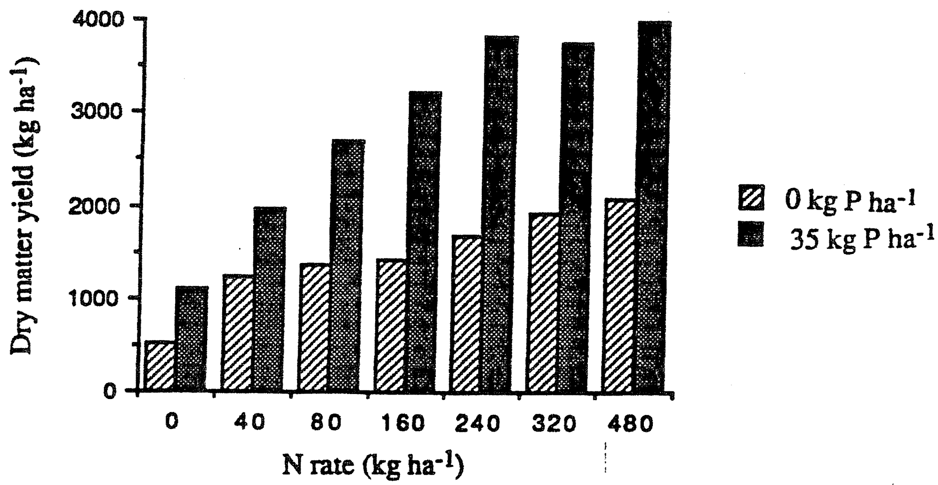


Figure 9. Interactive effect of N and P fertilizer on yield of bromegrass (from Ukrainetz, 1974).

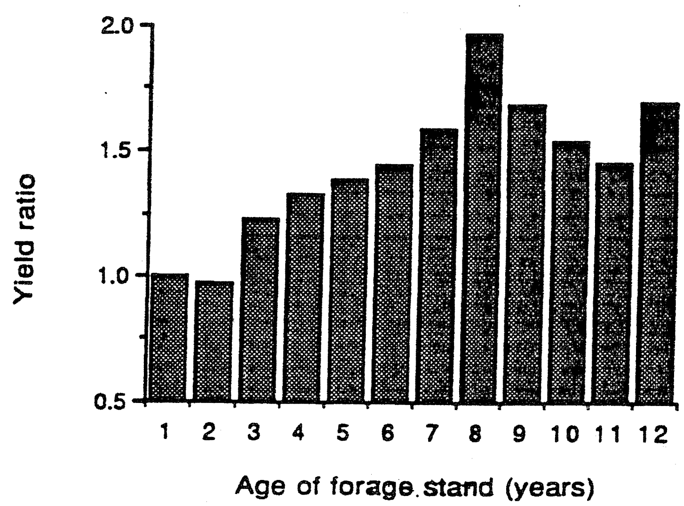


Figure 10. Yield ratio of fertilized (20 kg P $ha^{-1}$ annually) and unfertilized pasture over 12 years (from Nuttall et al., 1991).

Although P fertilization has not been advantageous in all cases, large yield responses have been documented for Grey Luvisolic soils (Wyatt, 1931; Cowell, 1989; Nuttall et al., 1991), sandy textured soils (Bailey, 1987a; Simons et al., 1991), and under irrigated conditions (Saskatchewan Institute of Pedology, 1970, 1977; Thompson et al., 1987). Alfalfa is often an important crop in these areas, emphasizing the potential importance of P fertilization.

There has been very little research to examine P fertilization of other forage legumes, including the clovers. Phosphorus fertilizer resulted in very large clover hay yield increases at the Breton plots in Alberta in the 1930s. Alsike, red and sweet clover responded much more strongly to P fertilizers than did either cereal crops or alfalfa (Wyatt, 1931; McAllister, 1934). Perhaps the biennial and short-lived perennial clovers may not have the superior ability of alfalfa to utilize soil P. Further research of this topic is warranted.

*Grass-alfalfa mixtures for hay:* The variable effect of P fertilizer on grasses and alfalfa grown alone is even more complex for mixed swards. Phosphorus fertilizer applied without N often favours the growth and dominance of alfalfa in the mixture (Table 8). When N is also applied, both grass and alfalfa benefit, and the grass often becomes dominant (Nuttall et al., 1980; Holt and Winkleman, 1983).

*Grass and alfalfa for seed production:* Very little research has been conducted to examine P requirements of grass or legume stands established for seed production. An early study of Grey soils in northeastern Saskatchewan measured higher alfalfa seed yields on one site, even when total yields were not affected. However, the response was not typical of all sites, nor were trends in P requirement explained (Rowles, 1938). Limited work in Manitoba also indicated a small and inconsistent response of alfalfa grown for seed to P fertilizer (Campbell, 1985). Russian wild ryegrass grown for seed at Saskatoon responded well to fertilizer P (Lawrence and Heinrichs, 1968). Stand persistence was maintained for 15 years when adequately fertilized, while unfertilized grass yielded little or no seed.

Table 8. Effect of annual P fertilization over 6 years on average yields of alfalfa and bromegrass and alfalfa ground cover in a mixed sward (from Bittman et al., 1991a).

| Fertilizer treatment | Alfalfa yield | Grass yield | Alfalfa ground cover |
|---|---|---|---|
| | ($t\ ha^{-1}$) | ($t\ ha^{-1}$) | (%) |
| 18 kg P $ha^{-1}\ yr^{-1}$ | 1.50 | 0.90 | 28.0 |
| Unfertilized | 0.77 | 0.67 | 20.7 |

Table 9. Yield of native fescue grass as affected by N and P fertilizer (from Read, 1969).

| Fertilizer applied | | Yield | Forage P concentration |
|---|---|---|---|
| N | P | | |
| ($kg\ ha^{-1}$) | | ($kg\ ha^{-1}$) | (%) |
| 0 | 0 | 3360 | 0.050 |
| 0 | 112 | 4320 | 0.084 |
| 112 | 0 | 5330 | 0.049 |
| 112 | 112 | 8950 | 0.085 |

Table 10. Average yield response of grass forage to two rates of P fertilizer at increasing levels of soil test P (0-15 cm), based on data from 22 sites in Manitoba and Saskatchewan (from Harapiak, 1979b).

| Available P | | Control yield[1] | Yield increase | |
|---|---|---|---|---|
| Range | Average | | 28 kg $P_2O_5\ ha^{-1}$a | 56 g $P_2O_5\ ha^{-1}$ |
| ($kg\ ha^{-1}$) | | ($kg\ ha^{-1}$) | ($kg\ ha^{-1}$) | |
| ≤11 | 8 | 3950 | 790 | 1100 |
| 12-17 | 15 | 3920 | 340 | 390 |
| 18-28 | 25 | 4770 | 190 | 480 |
| >28 | 38 | 5450 | 40 | -150 |

[1] Control treatment received 110 kg $ha^{-1}$ fertilizer N

The P fertilizer requirements of forage seed crops are not yet well understood. Once established, the extensive root system of perennial forages may utilize P more efficiently and from a greater depth. Unlike forages grown for hay, seed crops would remove very little P from the soil. Therefore, alfalfa and grasses grown for seed (forage not removed) would be expected to respond less frequently to P fertilizer, and a P deficiency would not likely develop with time. Nevertheless, seed yield may be affected more than total yield when soil P is deficient. This remains to be determined.

*Native rangeland:* Phosphorus uptake and dry matter yield is not often increased by fertilizer application to native rangeland on the prairies. The native system appears to cycle and utilize soil P very effectively. In addition, when seeded or native forage is used for pasture, the P-rich manure is returned directly to the soil (Nuttall, 1980). At seven native rangeland sites across western Canada, P fertilizer by itself or with N fertilizer provided only small and insignificant yield increases over several years (Kilcher et al., 1965). In contrast, a survey in southwestern Saskatchewan measured a response to P and N fertilizer at 33 of 40 rangeland sites (Read, 1969). At one site, the interactive effect of P and N fertilizer was very apparent; P applied alone increased native fescue growth by nearly 30% (Table 9). Overall, P additions are unlikely to increase yields of native rangeland unless applied with N fertilizer.

*Prediction of forage yield response to P fertilizer:* Tests for vailable soil P have repeatedly proven useful in the prediction of P requirements of forage. Extractable soil P is well related to P uptake by forages (Beaton et al., 1962; Krogman and Lutwick, 1964; Holt and Winkleman, 1983). The soil test level of available P also reflects past additions of P fertilizer, allowing adjustment for later applications (Read, 1969; Holt and Winkleman, 1982; Cowell, 1989). In most cases, a yield response can be predicted from measured P. In Saskatchewan and Manitoba, soil test P accurately defined fertilizer requirements of grass forage adequately supplied with N (Table 10).

## Forage Quality Response

Stimulation of plant growth by P may improve N uptake and protein production in a forage crop. Additions of P fertilizer have sharply increased forage protein quality in some research trials (Bailey, 1987a). Applications of P to bromegrass at two sites in Saskatchewan increased protein concentration only when applied with very high rates of N fertilizer (Ukrainetz and Campbell, 1988; Ukrainetz et al., 1988). Other research has measured no change or even decreases in forage protein content with P fertilization (McAllister, 1934; Saskatchewan Institute of Pedology, 1973, 1978; Ukrainetz, 1974; Lutwick and Smith, 1977; Bittman et al., 1991a). No research has measured the effect of P application on any forage quality parameter other than protein concentration. However, in view of the inconclusive data regarding protein concentration, P fertilization cannot be recommended solely to improve forage quality.

## Phosphorus Fertilizer Application Management

Forage seedling vigour is improved by adequate supplies of P, so sufficient P fertilizer should be applied in the year of establishment (Lawrence and Kilcher, 1972; Bittman et al., 1991). Since only low rates of fertilizer can be safely applied with the small and sensitive seeds of forages, higher rates should be banded away from the seed, or broadcast and incorporated.

Phosphorus fertilization of established stands of forage is more difficult. Fertilizer applied before seeding can be banded or incorporated into the soil without adversely affecting the forage stand. Subsurface placement of fertilizer after forage establishment may be detrimental. Banding fertilizer into established alfalfa with double disc drills or knife openers will damage the surface roots and crowns of the stand and reduce yields (Leyshon, 1982; Simons et al., 1991). The high draft requirement of conventional equipment in established forages also hinders band applications. Further development and testing of fertilizer applicators which cause less soil disturbance would prevent damage to forage stands and reduce energy costs of fertilizer application.

Fortunately, broadcast applications of P fertilizer on forages have proven successful. Phosphorus fertilizer will slowly move into the soil surface with physical disturbance by harvest equipment or grazing animals, soil cracking and swelling, and through leaching (Fig. 11). Near-surface alfalfa roots are therefore able to utilize broadcast P fertilizer.

An alternative to annual soil testing and P fertilizer application to forages is to use a single large fertilizer application to build up the pool of available soil P. In contrast to N fertilizers, large applications of P fertilizer presents no concern to feed quality or ground water contamination. In addition, the forage crop is always supplied with sufficient P with this strategy. Several field studies have demonstrated the value of residual fertilizer P from large single applications to maintain forage yields (Wyatt, 1931; Read, 1968; Holt and Winkleman, 1983; Cowell, 1989).

The relative efficiency of annual versus single applications of P fertilizer has not been well established. Research with irrigated alfalfa in Saskatchewan determined that yield increases from single additions of fertilizer could exceed annual applications at least over a short term (Fig. 12). Comparisons over a longer period of time and analyses of net return are required on this subject.

## SULPHUR FERTILIZATION

### Yield Response

*Alfalfa and clovers:* Alfalfa and clovers were among the first crops for which S deficiency was recognized in western Canada. In north-central Alberta, early studies on the Breton plots and on farmers' fields indicated severe S deficiencies in Grey Luvisolic soils (Table 11). Forage legumes were especially responsive to S fertilizers, with hay yield increases of over 100% common.

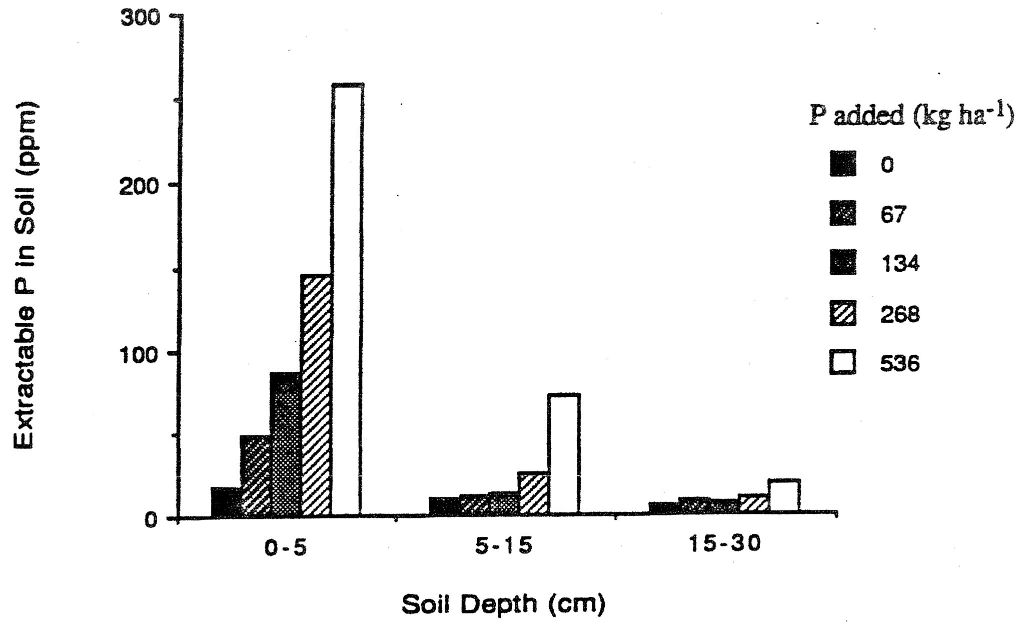


Figure 11. Soil test P at 3 depths after application of increasing rates of fertilizer P over 7 years to a grass forage stand (from Mahli et al., 1988).

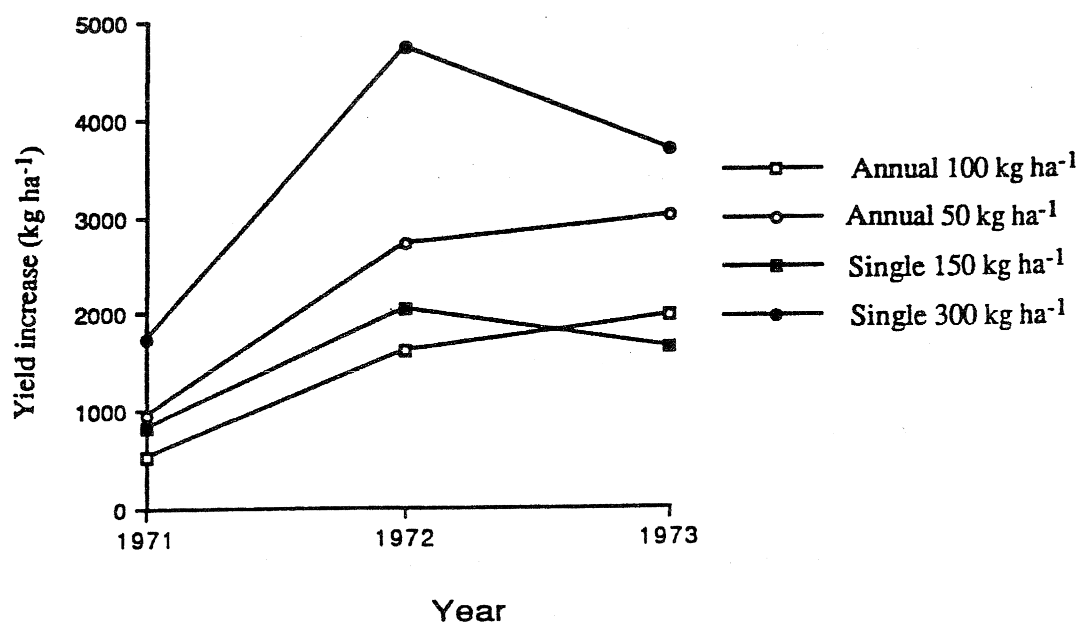


Figure 12. Alfalfa yield increases after annual fertilizer applications of 50 or 100 kg $P_2O_5$ $ha^{-1}$ or single applications of 100 or 300 kg $P_2O_5$ $ha^{-1}$ (compiled from annual Soil-Plant Nutrient Report, Saskatchewan Institute of Pedology, University of Saskatchewan, 1971-1973).

Table 11. Yields of alfalfa hay, grass hay and wheat seed in cooperative fertilizer trials on farms in the Grey soils of north-central Alberta, 1930-1947 (from Newton et al., 1948).

| Fertilizer Treatment | Grass No. trials | Grass Yield | Alfalfa No. trials | Alfalfa Yield | Wheat No. trials | Wheat Yield |
|---|---|---|---|---|---|---|
| | | (kg ha$^{-1}$) | | (kg ha$^{-1}$) | | (kg ha$^{-1}$) |
| Check | 23 | 2360 | 141 | 2060 | 29 | 1480 |
| Ammonium phosphate | 5 | 3220 | 5 | 2730 | 9 | 1780 |
| Triple superphosphate | -- | -- | 15 | 3000 | 4 | 1950 |
| Ammonium sulphate | 22 | 4150 | 130 | 4400 | 34 | 1940 |
| Gypsum | 6 | 3380 | 54 | 4070 | 8 | 1510 |

Table 12. Effect of increasing sulphate fertilizer on yield of legume hay (alfalfa, red clover or alsike clover) at 20 S responsive sites in central Alberta (from Walker and Doornenbal, 1972).

| Fertilizer rate | Hay yields: Average yield | Hay yields: Minimum yield | Hay yields: Maximum yield |
|---|---|---|---|
| (kg S ha$^{-1}$) | | (kg ha$^{-1}$) | |
| 0 | 1210 | 270 | 2780 |
| 5.6 | 2040 | 630 | 4720 |
| 22.4 | 2520 | 680 | 4950 |
| 44.8 | 2370 | 650 | 4490 |

The importance of forage legumes in the developing agriculture of the northern Grey soil zone underscored the need for continued S research with these crops. Experiments with radioactive S confirmed the greater S requirement of legumes. Sulphur fertilizer doubled average hay yields on deficient soils, and maximum yields were always attained with additions of only 11 kg S $ha^{-1}$ in a sulphate form. Previous rotational and fertilization practices were recognized as important factors in determining the probability of a yield increase (Bentley et al., 1955). A subsequent study of alfalfa and clover response to S fertilizer at 157 locations in central Alberta confirmed that forage responses to S were not necessarily confined to specific soil series or geographic areas (Walker and Bentley, 1961). Although Grey soils were certainly more often deficient in S, this was not always true, and some Chernozemic soils also responded to S fertilization. Sulphur deficiency was more severe in older stands of alfalfa, a result of continued uptake and removal of soil S (Nyborg, 1968). Research continued to develop guidelines to predict S response, and the extractable level of soil sulphate was found to be useful. Again, only small applications of sulphate were needed, regardless of the magnitude of yield response (Walker and Doornenbal, 1972).

Although S research on forages in Saskatchewan has not been as extensive as in Alberta, similar conclusions have been drawn. Sulphur deficiencies in alfalfa were recognized early in coarse textured Grey wooded soils in northeastern Saskatchewan in the 1940s, and have since been documented (Shalin, 1948). Certain Grey soils, such as the Loon River association, appear typically S deficient. Other Grey Luvisolic soils often contain sufficient S for crop growth (Cairns and Carson, 1961). Chernozemic soils may occasionally require added S fertilizer (Nuttall, 1985a ). Forage legumes have proven more sensitive to S deficiency than cereal crops (Ukrainetz, 1979). Again, the coincidental importance of forage legumes in areas of potentially S deficient soils has been recognized.

Potentially S deficient soils have been well defined in Manitoba, and large yield responses have been reported for alfalfa (Beaton and Soper, 1986; Bailey, 1986). Sulphur deficiencies are most likely to occur where soils have developed in conditions in which leaching processes are significant. Medium and coarse textured Grey Luvisolic soils and coarse textured Chernozemic soils are most susceptible.

Sulphur response curves for forage legumes have not been well described, despite very large potential yield increases. Small application rates of sulphate fertilizers similar to previous crop removal rates (2 to 3 kg S $t^{-1}$ hay) have proven sufficient to maximize yields in most cases (Table 12). Little research has compared the relative S requirements of alfalfa and clovers, nor established the effect of available soil water or growing conditions on plant S requirements. No data were found that described S fertilization of forage legumes grown for seed production in western Canada. The benefits of S fertilizer application are well documented, but better information is needed to ensure maximum yields under all soil, climatic and cropping conditions.

*Grasses:* Grasses require less S than legumes for normal growth. Most grass species remove 1.5 to 2.5 kg of S per tonne of hay. For this reason, few research projects have examined S requirements of perennial grasses in western Canada, and only small yield increases have been reported (Bailey, 1974; Harapiak, 1979b). Unfortunately, only a few of these trials were conducted on Grey wooded soils. Sulphur applied to bromegrass and bromegrass-alfalfa mixtures grown on Grey Luvisolic soils in Saskatchewan produced significant yield increases when applied with sufficient N fertilizer (Nuttall et al., 1991; Ukrainetz et al., 1988). Although S deficiencies in grasses are less frequent than for forage legumes, researchers and farmers should not overlook S in complete fertilizer programs.

*Prediction of forage yield response:* Prediction of crop response to S fertilizer has been based on both soil and tissue analysis (Maynard et al., 1982). In particular, the substantial data from alfalfa S research has provided accurate criteria to delineate areas of the prairies requiring additional S. Data for grasses have not been extensively published.

Available soil sulphate has proven to be a dependable measure of S fertility. In an extensive field program in Alberta more than 95% of forage legume fields with less than

2 ppm of extractable sulphate-S in the 0-15 cm depth were S deficient. In fields with over 4 ppm sulphate, less than 10% were deficient (Fig. 13). The accuracy of prediction of a S deficiency based on extractable sulphate increased from 79 to 86 percent as sampling depth increased from 15 to 30 cm.

As observed for cereals and oilseeds (*Chapter 6*), several studies have demonstrated a strong N-S interaction for forages. A wide ratio of total or available soil N to soil S may indicate a S deficiency. Examination of this ratio may improve our predictions based solely on extractable sulphate. Based on Manitoba research, a critical soil N:S ratio of 9 has been suggested for alfalfa (Bailey, 1986).

Plant tissue analysis may also prove useful for understanding S requirements, and may be a more accurate indicator than soil analysis (Nuttall, 1985b). A total S content of 0.20 to 0.25% appears marginal for alfalfa (Cairns and Carson, 1961; Walker and Bentley, 1961). A tissue N:S ratio greater than 12 for alfalfa and 14 for clovers may indicate a S deficiency (Table 13).

## Forage Quality Response

As S is a component of certain proteins, S deficiency will lead to some reduction in protein content and forage quality. Studies in western Canada have verified a consistent increase of forage protein with addition of S fertilizer, although this effect is usually small (Bentley et al., 1955; Bailey, 1974, 1978). A comparison of S deficient and S sufficient Grey wooded soils in northwestern Saskatchewan found little relationship between yield response to S fertilizer and protein concentration (Table 14).

Very low levels of selenium (Se) have been measured in forages grown in some areas of western Canada. Although crop growth is not affected, Se deficiencies may lead to degenerative white muscle disease of livestock. Selenium is most often deficient in coarse textured Grey wooded soils, often where S is also deficient. Unfortunately, additions of S fertilizer antagonize Se uptake by plants (Mahli et al., 1987). Although Se

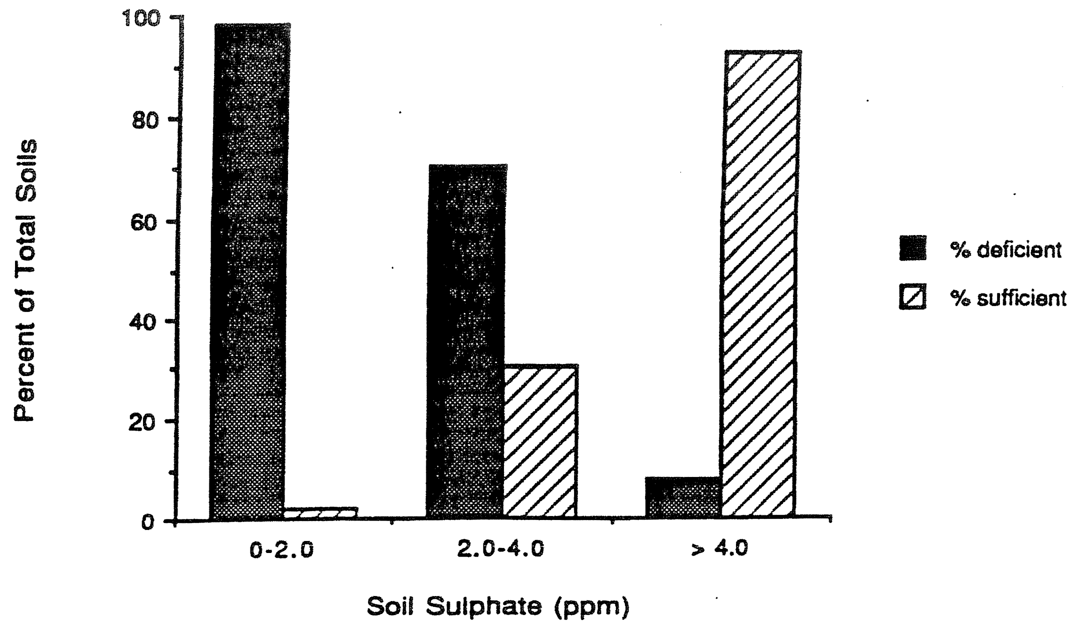


Figure 13. Percent S deficient and S sufficient soils for increasing levels of soil sulphate in 93 soils in Alberta. Sulphur deficiency or sufficiency was based on field response of forage legumes to S fertilizer. Water-extractable soil sulphate from the 0-15 cm depth was measured by $BaCl_2$ (from Walker and Doornenbal, 1972).

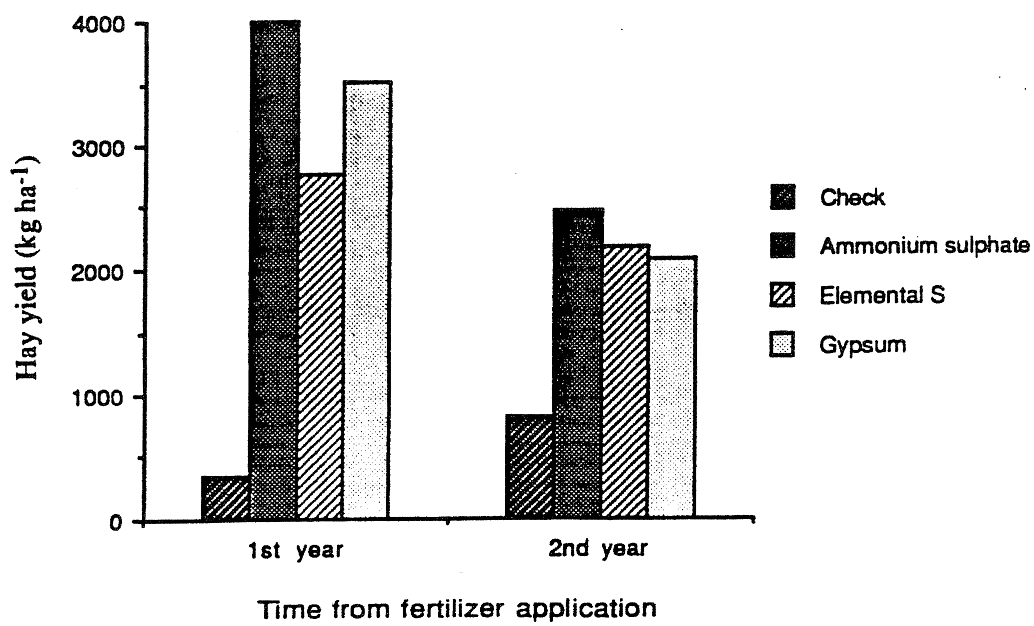


Figure 14. Yield response of alfalfa to various S fertilizers in the first and second year after fertilizer application (from Ukrainetz, 1969).

Table 13. Sulphur status of fertilized and unfertilized forage legumes grown on S deficient and S sufficient soil (from Walker and Bentley, 1961).

| Soil S status | Fertilizer treatment | Tissue S | Tissue N/S |
|---|---|---|---|
| | | (%) | |
| | *Alfalfa* | | |
| Deficient | Check | 0.15 | 19.6 |
| | 22 kg S ha$^{-1}$ | 0.26 | 12.4 |
| Sufficient | Check | 0.24 | 12.8 |
| | 22 kg S ha$^{-1}$ | 0.38 | 11.5 |
| | *Clover* | | |
| Deficient | Check | 0.11 | 20.6 |
| | 22 kg S ha$^{-1}$ | 0.18 | 15.2 |
| Sufficient | Check | 0.18 | 16.8 |
| | 22 kg S ha$^{-1}$ | 0.21 | 15.2 |

Table 14. Alfalfa yield and composition as affected by fertilizer applied to S deficient (Loon River) and S sufficient (Garrick) soils (from Cairns and Carson, 1961).

| Fertilizer treatment | Hay yield | Total N | Protein N | Total S | Protein S |
|---|---|---|---|---|---|
| | (kg ha$^{-1}$) | % | % | % | % |
| | | | *Loon River soil* | | |
| Check | 1036 | 3.01 | 2.08 | 0.17 | 0.07 |
| With S | 1453 | 3.32 | 2.29 | 0.28 | 0.09 |
| | | | *Garrick soil* | | |
| Check | 2787 | 2.72 | 1.92 | 0.21 | 0.08 |
| With S | 2758 | 2.97 | 1.92 | 0.24 | 0.04 |

deficiency in animals can be remedied through mineral supplements or injections, the farmer must be aware of this potential problem when adding S fertilizers to forage crops.

**Sulphur Fertilizer Application Management**

Most research dealing with S fertilizer management has focussed on the fertilizer source. Recommendations for S fertilizer are usually based on applications of readily available sulphate forms of fertilizer such as ammonium sulphate and K sulphate. Early studies confirmed that elemental S and gypsum (calcium sulphate) were less effective fertilizers, due to their slow release of sulphates available for plant uptake in the year of application. This premise has been demonstrated several times in research (Table 15).

In the year of application, gypsum has consistently been over 80% as effective as readily soluble S fertilizers. Elemental S fertilizer has performed less effectively and less efficiently than sulphates. However, in individual cases in these studies, elemental S has been as effective as sulphates. The performance of elemental S depends on the physical form of fertilizer used and on field conditions. Smaller fertilizer particles increase the rate of S oxidation to sulphate (Bailey, 1978). In a pasture environment, trampling by grazing animals may increase fertilizer disintegration and improve uptake with time. Elemental S has proven effective for pasture fertilization, though only a few experiments have compared S fertilizers over a suitably long period of time (Nuttall et al., 1991). However, some work has suggested the availability of elemental S sharply increases just one year after application (Fig. 14). For the purpose of forage fertilization, a better understanding of long-term S fertilizer dynamics is required.

Timing and placement of S fertilizer for forages have received only limited attention in research. Sulphate applied to the soil surface is readily leached into the soil. Although forages are quite capable of using available S from depth, there appears to be little advantage to subsurface applications of sulphate fertilizers (Fig. 15). Placement of gypsum or elemental S has not been assessed. Early application of elemental S and gypsum will

Table 15. Relative efficiency of elemental S and gypsum as S fertilizers compared to readily soluble sulphate fertilizers in terms of ability to increase forage crop yields in the year of fertilizer application, from various studies in western Canada.

| Source | Fertilizer efficiency relative to sulphate | |
|---|---|---|
| | Elemental S | Gypsum |
| | (%) | |
| Shalin, 1948 | 59 | 86 |
| Newton et al., 1948 | 63 | 84 |
| Cairns and Carson, 1961 | 31 | 83 |
| Bently et al., 1955 | 19 | 94 |
| Ukrainetz, 1969 | 66 | 87 |

Table 16. Yield of timothy and reed canarygrass on a peat soil fertilized with combinations of N, P, and K fertilizers (from Mahli and Dew, 1987).

| Fertilizer applied | | | Hay yield | |
|---|---|---|---|---|
| N | P | K | Timothy | Reed canarygrass |
| ($kg\ ha^{-1}$) | | | ($t\ ha^{-1}$) | |
| 0 | 0 | 0 | 1.50 | 1.76 |
| 56 | 0 | 0 | 2.74 | 2.60 |
| 56 | 20 | 0 | 2.87 | 3.19 |
| 56 | 20 | 38 | 3.60 | 3.82 |

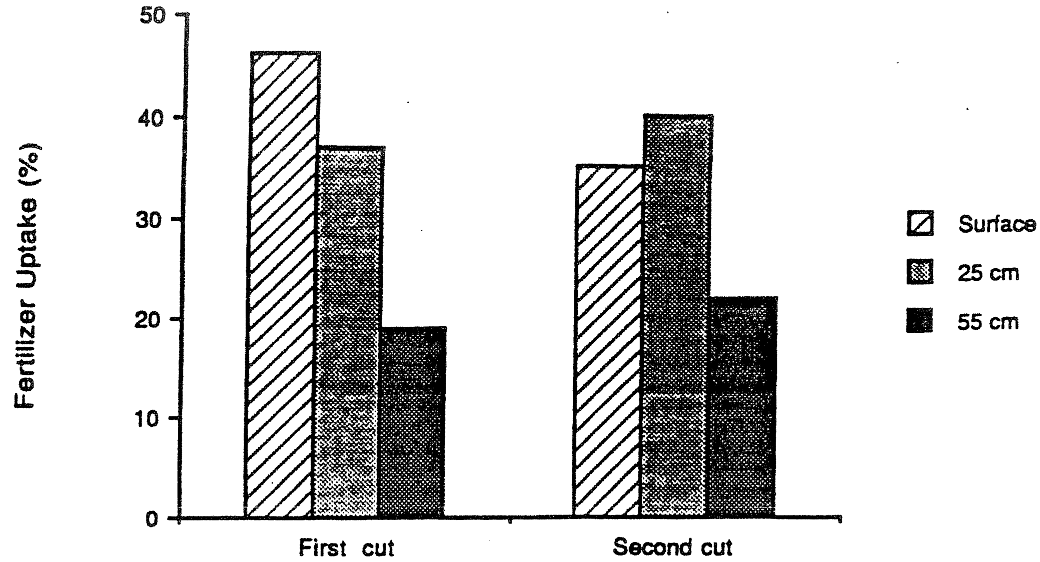


Figure 15. Percentage of fertilizer S in alfalfa for increasing depths of sulphate fertilizer placement (from Bentley et al., 1955).

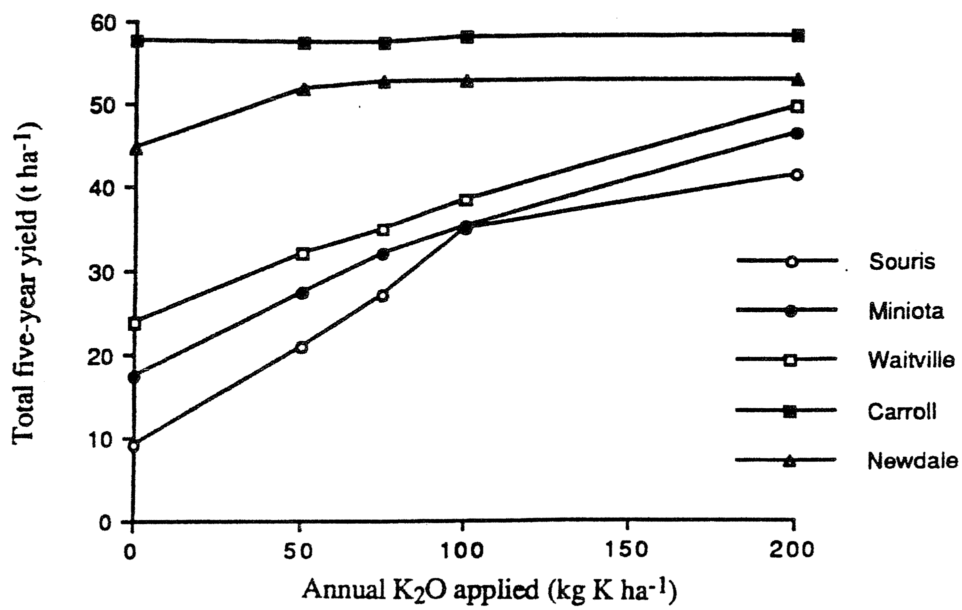


Figure 16. Total alfalfa yield over a five year period with increasing rates of K applied annually to five sites in Manitoba. The texture and exchangeable K of each site were; Souris (sandy loam, 50 kg K $ha^{-1}$), Miniota (sandy loam, 125 kg K $ha^{-1}$), Waitville (sandy loam, 310 kg K $ha^{-1}$), Carroll (clay loam, 695 kg K $ha^{-1}$), and Newdale (clay loam, 972 kg K $ha^{-1}$) (from Bailey, 1983).

allow time for release of available S. These fertilizers should be applied in the establishment year of the forage for maximum effectiveness. A further yield increase may be realized if the fertilizers are applied in the fall previous to establishment (Shalin, 1948). Advanced application for sulphate fertilizers is not required, as these fertilizers quickly remedy a S deficiency.

## POTASSIUM FERTILIZATION

### Yield Response

Most soils of western Canada have sufficient available K for normal crop growth (*Chapters 5 and 8*). Only small pockets of very coarse textured Grey Luvisolic soils consistently require additions of K fertilizer. This general sufficiency of soil K has precluded extensive research of K fertilizer management for forages on the prairies, despite the importance of these crops in typically K deficient areas.

A summary of various K research and demonstration trials with forages in Alberta found no significant yield increases in 47 site-years (Robertson, 1979). Irrigated fields of various soil texture and extractable K levels in the Brown and Dark Brown soil zones of southern Alberta showed no response to K fertilizer over a 4-year field experiment or in growth chamber experiments (MacKay and Carefoot, 1987). At a number of sites in the Lake Diefenbaker irrigation project of Saskatchewan, alfalfa did not benefit from K fertilization over a three year period (Saskatchewan Institute of Pedology Annual Reports, 1971-1973). Grass forage trials on typical Chernozemic soils in Manitoba and Saskatchewan also found no consistent response to K fertilizer (Harapiak, 1979b).

In contrast, large alfalfa yield increases have been measured on sandy Chernozemic soils in Manitoba (Fig. 16). Pockets of coarse textured Grey Luvisolic and Grey Black Chernozemic soils in northeastern Saskatchewan are also recognized as K deficient (Pulkinen, 1979). As soil K exists almost entirely in inorganic forms, Organic soils are chronically K deficient. Complete fertilizer additions (i.e., N-P-K) are essential for forage production on many of these soils (Table 16).

Although alfalfa and grass tissue does not contain a higher percentage of K than most other crops, complete removal of the top growth over a number of years may eventually deplete soil reserves of exchangeable K to a soil maintenance level unless supplemented with fertilizer (Fig. 17). Therefore, older stands are most likely to be K deficient. Stand density and yield will slowly decline as winter-kill thins the weakened plants (Bailey, 1987a). In time, deficiencies may even develop on normally K-sufficient soils (MacKay and Carefoot, 1987; Cowell, 1989). For the same reason, the yield of second and third cuts of forage will be increased more by additions of K than the first hay cut of the year (Bailey, 1983).

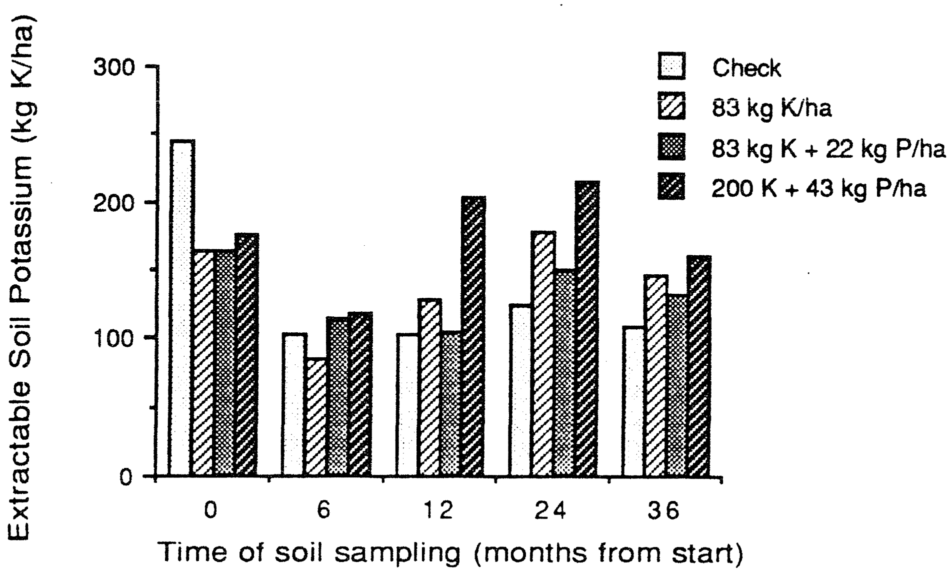


Figure 17. Available soil K as affected by alfalfa uptake and annual fertilizer additions over a 36 month period (from Thompson et al., 1987).

Few K rate studies are available to adequately assess forage response to K fertilizer in real or economic terms. About 15 to 25 kg $ha^{-1}$ of K is removed per tonne of hay, so fertilizer rates exceeding 100 kg K $ha^{-1}$ are often required. Prediction of K requirements depends on soil or plant analysis. Although soil extractions are certainly useful, these measurements do not always accurately reflect previous K fertilizer applications nor fertilizer requirements (Harapiak, 1979b; Bailey, 1983; MacKay and Carefoot, 1987; Cowell, 1989). If a K deficiency is suspected, plant tissue analysis and field check strips might be valuable to verify fertilizer response.

### Quality Response

Potassium is required for biological $N_2$ fixation and for protein synthesis. Enzyme activation and carbohydrate transport to root nodules are key processes which involve K and which directly affect N fixation and therefore protein synthesis. Thus $N_2$ fixation may be more sensitive to K deficiency than is crop growth. Protein concentration is sometimes improved with K fertilization, even when yield is not affected (Pulkinen, 1979; Bailey, 1983).

### Potassium Fertilizer Application Management

Essentially no western Canadian research has yet examined K fertilizer management for forages. Broadcast applications are normally made, because reasonable rates cannot be seed placed with sensitive forage seed. The relative efficiency of soil incorporated K prior to forage crop establishment and broadcast applications to established stands is not known. A strategy of rapidly building up the available soil K pool also requires evaluation. Although only a small area of western Canada is K deficient, forage crop requirements for this essential nutrient in certain soil types suggest a need for more research in this area.

## RESEARCH PRIORITIES

General guidelines for optimum fertilization of forage crops, including dryland and irrigated hay and pasture, are based on well designed and widespread field fertilizer testing programs in western Canada. Over much of the prairie rangeland, frequent moisture deficits limit yields and response to fertilizer nutrients. However, substantial areas of pasture and hay land have been neglected in terms of research of nutrient requirements, and farmers may benefit from a better understanding and application of research data.

In review of the fertilizer research conducted with forages in western Canada, the following is a short list of research projects which could lead to significant increases in forage production:

1. A revision of current N recommendations for grass hay crops is required, with consideration of hay yield and quality, hay price and cost of fertilizer application, grass type and growing conditions.
2. Macronutrient requirements of forage crops grown for seed has been largely neglected; this research is needed to predict N requirements of grass seed crops and P requirements of legume seed crops.
3. Fertilizer management of grazing land requires attention. The effect of fertilizers on plant species (native and introduced) dynamics and on grazing preference should not be overlooked.
4. Phosphorus requirements of hay crops, especially of older stands, should be better established, including comparisons of single and annual applications of P fertilizer.
5. Placement of fertilizers on forages has so far been largely limited to broadcast applications. These must be further compared to band and nest placements, for both newly established and older forage crops.
6. Although S and K nutrient deficiencies are uncommon on the prairies, forage crops often play an important role in areas deficient in these nutrients. At least, the soils which potentially require S and K fertilizer for forage production should be better delineated. Further comparison of various forms of S fertilizer under various forage crop scenarios (seed production, hay production, pasture land) may prove useful.

## REFERENCES

Alberta Agriculture. 1989. Alberta Agricultural Statistics Yearbook. Pub. Alberta Agriculture, Statistics Branch, Edmonton, Alberta.

Alberta Agriculture. 1981. Forage Manual. Publication No. 120/20-4.

Alberta Agriculture. 1987. Processed Alfalfa Summary. Market Situation and Outlook, Issue 2.

Bailey, L.D. 1974. The effects of N source on the yield and chemical composition of 4 grasses. pp. 180-193. Proc. 1974 Man. Soil Sci. Workshop.

Bailey, L.D. 1978. Sulphur status of some western Manitoba soils. pp. 101-109. Proc. 1978 Man. Soil Sci. Workshop.

Bailey, L.D. 1983. Effects of potassium fertilizer and fall harvests on alfalfa grown on the eastern Canadian prairies. Can. J. Soil Sci. 63: 211-219.

Bailey, L.D. 1986. The sulphur status of eastern Canadian prairie soils: sulphur response and requirements of alfalfa (*Medicago sativa* L.), rape ( *Brassica napus* L.) and barley (*Hordeum vulgare* L.). Can. J. Soil Sci. 66: 209-216.

Bailey, L.D. 1987a. Fertilizing alfalfa forage. Manitoba Agriculture Soil Facts. Agdex 541.

Bailey, L.D. 1987b. Sulphur status of Manitoba soils: relationship to $SO_4^{2-}$ availability and plant growth. pp. 72-78. Proc. 1987 Man. Soil Sci. Workshop.

Beaton, J.D. and Soper, R.J. 1986. Plant response to sulfur in western Canada. pp. 375-403. In: Sulfur In Agriculture. Amer. Soc. Agron. Mon. no. 27.

Beaton, J.D., Read, D.W.L., and Hinman, W.C. 1962. Phosphrus uptake as influenced by phosphate source and moisture. Can. J. Soil Sci. 42: 254-265.

Bently, C.F., Hoff, D.J., and Scott, D.B. 1955. Fertilizer studies with radioactive sulphur. Can. J. Agric. Sci. 35: 264-281.

Bittman, S., Pulkinen, D.A., and Waddington, J. 1991a. Effect of N and P fertilizer on establishment of alfalfa with a wheat companion crop. Can. J. Plant Sci. 71: 105-113.

Bittman, S., Waddington, J., and McCartney, D.H. 1991b. Performance of alfalfa strains grown in mixture with smooth bromegrass as affected by management. Can. J. Plant Sci. 71: 1029-1037.

Cairns, R.R. 1968. Various forms of nitrogen fertilizer for bromegrass on a solonetzic soil. Can. J. Soil Sci. 48: 297-300.

Cairns, R.R. and Carson, R.B. 1961. Effect of sulphur treatments on yield and nitrogen and sulphur content of alfalfa grown on sulphur-deficient and sulphur-sufficient grey wooded soils. Can. J. Plant Sci. 41: 709-715.

Cairns, R.R., Bowser, W.E., Milne, R.A., and Chang, P.C. 1967. Effects of nitrogen fertilization of bromegrass grown on solonetzic soils. Can. J. Soil Sci. 47: 1-6.

Campbell, C.A., Leyshon, A.J., Ukrainetz, H., and Zentner, R.P. 1986. Time of application and source of nitrogen fertilizer on yield, quality, nitrogen recovery, and net returns for dryland forage grasses. Can. J. Plant Sci. 66: 915-931.

Campbell, D.C. 1985. Effects of phosphorus rates on alfalfa seed yields. pp. 118-123. Proc. 1985 Man. Soil Sci. Workshop.

Campbell. C.A., Ukrainetz, H., and Zentner, R.P. 1988. A 9-yr study of the effect of N on forage yields and N recovery by bromegrass grown on a gray Luvisol in northwestern Saskatchewan. pp. 201-210. Proc. 1988 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.

Cooke, D.A., Beacom, S.E., and Dawley, W.K. 1968. Response of six-year-old grass-alfalfa pastures to nitrogen fertilizer in northeastern Saskatchewan. Can. J. Plant Sci. 48: 166-173.

Cowell, L.E. 1989. Alfalfa forage response to residual P and K fertilizer. pp. 2-10. 1989 Field Research Report. Dept. Soil Science, Univ. of Saskatchewan, Saskatoon, Sask.

Dean, J.R. and Clark, K.W. 1972. Nitrogen fertilization of reed canarygrass and its effects on production and mineral element content. Can. J. Plant Sci. 52: 325-331.

Environment Canada. 1976. Canada Land Inventory. Soil Capability for Agriculture, 1:1,000,000 maps for Alberta, Saskatchewan, and Manitoba.

Fairey, N.A. 1991. Effects of nitrogen fertilizer, cuting frequency, and companion legume on herbage production and quality of four grasses. Can. J. Plant Sci. 74: 717-725.

Grant, C.A., Simons, R.G., and Bailey, L.D. 1992. P and K fertilizer placement in alfalfa. pp. 219-224. Proc. 1992 Great Plains Soil Fertility Conference, Denver, Colorado.

Harapiak, J.T. 1979a. Comparison of fall and spring applied nitrogen. pp. 37-43. Proc. 1979 Alberta Soil Science Meetings.

Harapiak, J.T. 1979b. Summary of WCFL grass forage research in Saskatchewan and western Manitoba. pp. 162-171. Proc. 1979 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.

Harapiak, J.T., Mahli, S.S., Nyborg, M., and Flore, N.A. 1992. Dry matter yield and N recovery from bromegrass in south-central Alberta as affected by rate of long-term N application. Comm. Soil Sci. Plant Anal. In Press.

Holt, N.W. 1983. Yield and composition of bromegrass-alfalfa as affected by ammonium phosphate fertilizers. Can. J. Plant Sci. 63: 169-172.

Holt, N.W. and Winkleman, G.E. 1983. Availability of residual fertilizer phosphorus as measured by bromegrass-alfalfa dryt matter and phosphorus yield and by extractable soil phosphorus. Can. J. Plant. Sci. 63: 173-181.

Holt, N.W. and Zentner, R.P. 1985. Effects of applying inorganic fertilizer and farmyard manure on forage production and economic returns in east-central Saskatchewan. Can. J. Plant Sci. 65: 597-607.

Holt, N.W., Zentner, R.P., Lawrence, T., Kilcher, M.R., and Peters, H. 1991. Effect of nitrogen fertilizer on beef production and forage quality of Russian wildrye. Can. J. Anim. Sci. 71: 833-843.

Johnston, A., Smith, A.D., Lutwick, L.E., and Smoliak, S. 1968. Fertilizer response of native and seeded ranges. Can. J. Plant Sci. 48: 467-472.

Johnston, A., Smopliak, S., Smith, A.D., and Lutwick, L.E. 1967. Improvement of southeastern Alberta range with fertilizers. Can. J. Plant Sci. 47: 671-678.

Kilcher, M.R. 1958. Fertilizer effects on hay production of three cultivated grasses in southern Saskatchewan. J. Range Manag. 11: 231-234.

Kilcher, M.R., Smoliak, S., Hubbard, W.A., Johnston, A., Gross, A.T.H., and McCurdy. E.V. 1965. Effects of inorganic nitrogen and phosphorus fertilizers on selected sites of native grassland in western Canada. Can. J. Plant Sci. 45: 229-236.

Knowles, R.P. and Cooke, D.A. 1952. Response of bromegrass to nitrogen fertilizers. Sci. Agric. 32: 548-554.

Krogman, K.K. and Lutwick, L.E. 1964. Uptake of nitrogen by wheat, and phosphorus by alfalfa, from some grassland soils of southern Alberta. Can. J. Soil Sci. 44: 304-309.

Lawrence, T. 1973. Productivity of intermediate wheatgrass as influenced by date of initial cutting, height of cutting, and N fertilizer. Can. J. Plant Sci. 53: 295-301.

Lawrence, T. and Ashford, R. 1968. Effect of nitrogen fertilizer and clipping frequency on the dry matter yield and persistency of intermediate wheatgrass. Can. J. Plant Sci. 49: 435-446.

Lawrence, T. and Heinrichs, D.H. 1968. Long-term effects of row spacing and fertilizer on the productivity of Russian wild ryegrass. Can. J. Plant Sci. 48: 75-84.

Lawrence, T. and Kilcher, M.R. 1972. Emergence, seedling growth, and yield of altai wild ryegrass and other grasses as influenced by soil temperature and fertility. Can. J. Plant Sci. 52: 795-800.

Lawrence, T. and Knipfel, J.E. 1981. Yield and digestibility of crested wheatgrass and Russian and Altai wild ryegrasses as influenced by N fertilization and date of first cutting. Can. J. Plant Sci. 61: 609-618.

Lawrence, T., Korven, H.C., Winkleman, G.E., and Warder, F.G. 1980. The productivity and chemical composition of altai wild ryegrass as influenced by time of irrigation and time and rate of fertilization. Can. J. Plant Sci. 60: 1179-1189.

Lawrence, T., Warder, F.G., and Ashford, R. 1968. Nitrate accumulation in intermediate wheatgrass. Can. J. Plant Sci. 48: 85-88.

Lawrence, T., Winkleman, G.E., and Warder, F.G. 1982. The chemical composition of Russian and Altai wild ryegrass and crested wheatgrass as influenced by N fertilization and date of harvest. Can. J. Plant Sci. 62: 373-390.

Lawrence, T., Warder, F.G., and Ashford, R. 1970. Effect of fertilizer nitrogen and clipping frequency on the crude protein content, crude protein yield and apparent nitrogen recovery of intermediate wheatgrass. Can. J. Plant Sci. 50: 723-730.

Leyshon, A.J. 1982. Deleterious effects on yield of drilling fertilizer into established alfalfa stands. Agron. J. 74: 741-743.

Leyshon, A.J. 1985. Nitrogen transfer from alfalfa to grass. pp. 206-212. Proc. 1985 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.

Leyshon, A.J. 1991. Effect of rate of nitrogen fertilizer on the above- and below-ground biomass of irrigated bromegrass in southwest Saskatchewan. Can. J. Plant Sci. 71: 1057-1067.

Lutwick, L.E. and Smith, A.D. 1977. Yield and composition of alfalfa and crested wheatgrass, grown singly and in mixture, as affected by N and P fertilizers. Can. J. Plant Sci. 57: 1077-1083.

Lutwick, L.E. and Smith, A.D. 1979. Yield and N uptake by seven perennial grass species as affected by high rates of N fertilizer. J. Range Manage. 32: 433-436.

MacKay, D.C. and Carefoot, J.M. 1987. Potassium status of irrigated Brown Chernozemic soils of southern Alberta. Can. J. Soil Sci. 67: 877-891.

Mahli, S.S. and Dew, D. 1987. Effect of fertilization of peat soils on hay yields. Agriculture Canada, Canadex 120.530.

Mahli, S.S. and Ukrainetz, D. 1990. Effect of band spacing of urea on dry matter and crude protein yield of bromegrass. Fert. Res. 21: 185-187.

Mahli, S.S., Baron, V.S., and McBeath, D.K. 1987. Economics of N fertilization of bromegrass for hay in central Alberta. Can. J. Plant Sci. 67: 1105-1109.

Mahli, S.S., D.K. McBeath, Walker, D.R., and Robertson, J.A. 1988. Fate of surface-applied phosphorus on established forage stands. Agriculture Canada, Canadex 120.542.

Mahli, S.S., Dick, A.C., and Walker, D.R. 1987. Effect of sulphur fertilization on selenium concentration of forages. Agriculture Canada, Canadex 120.540.

Mahli, S.S., Harapiak, J.T., Nyborg, M., and Flore, N.A. 1992. Dry matter yield and N recovery from bromegrass in south-central Alberta as affected by time of application of urea and ammonium nitrate. Comm. Soil Sci. and Plant Anal. In Press.

Mahli, S.S., McBeath, D.K., and Baron, V.S. 1986. Effects of nitrogen application on yield and quality of bromegrass hay in central Alberta. Can. J. Plant Sci. 66: 609-616.

Mahli, S.S., Walker, D.R., Doran, W.J., and Bowman, G.H. 1987. Relative productivity of a fertilized and an unfertilized pasture. Agriculture Canada, Canadex 130.21.

Manitoba Agriculture. 1989. Manitoba Agricultural Statistics Yearbook. Pub. Manitoba Agriculture, Winnipeg, Man.

Manitoba Agriculture. 1988. Field crop production guide for Manitoba 1988-1990. Manitoba Agriculture, Winnipeg, Man.

Maynard, D.G., Stewart, J.W.B., and Bettany, J.R. 1982. Diagnosis of sulphur deficiency in plants and soils. pp. 207-228. Proc. 1982 Alberta Soil Science Meetings.

McAllister, R.E. 1934. The effect of fertilizers on the yield and composition of crops from the wooded soils of Alberta. Sci. Agric. 14: 249-256.

McCaughey, W.P., Smith, E.G., and Gross, A.T.H. 1990. Economics of N-fertilization of dryland grasses for hay production in southwestern Manitoba. Can. J. Plant Sci. 70: 559-563.

Newton, J.D., Ward, A.S., and Bentley, C.F. 1948. Wooded soils and their management. Bull. no. 21, revised. Dept. of Soils, University of Alberta, Edmonton, Alta.

Nuttall, W.F. 1976. Effect of soil moisture tension and amendments on yields and on herbage N, P, and S concentrations of alfalfa. Agron. J. 68: 741-744.

Nuttall, W.F. 1980. Effect of nitrogen and phosphorus fertilizers on a bromegrass and alfalfa mixture grown under two systems of pasture management. II. Nitrogen and phosphorus uptake and concentration in herbage. Agron. J. 72: 295-298.

Nuttall, W.F. 1985a. Effect of N, P, and S fertilizers on alfalfa grown on three soil types in northeastern Sasktchewan. I. Yield and soil tests. Agron. J. 77: 41-46.

Nuttall, W.F. 1985b. Effect of N, P, and S fertilizers on alfalfa grown on three soil types in northeastern Saskatchewan. II. Nitrogen, P, and S uptake and concentration in herbage. Agron. J. 77: 224-228.

Nuttall, W.F., Cooke, D.A., Waddington, J., and Robertson, J.A. 1980. Effect of nitrogen and phosphorus fertilizers on a bromegrass and alfalfa mixture grown under two systems of pasture management. I. Yield, percentage legume in sward, and soil tests. Agron. J. 72: 289-294.

Nuttall, W.F., McCartney, D.H., Bittman, S., Horton, P.R., and Waddington, J. 1991. The effect of N, P, S fertilizer, temperature and precipitation on the yield of bromegrass and alfalfa pasture established on a Luvisolic soil. Can. J. Plant Sci. 71: 1047-1055.

Nyborg, M. 1968. Sulfur deficiency in cereal grains. Can. J. Soil Sci. 48: 37-41.

Penney, D.C., Mahli, S.S., and Kryzanowski, L. 1990. Effect of rate and source of N fertilizer on yield, quality and N recovery of bromegrass grown for hay. Fert. Res. 25: 159-166.

Power, J.F. 1967. The effect of moisture on fertilizer nitrogen immobilization in grasslands. Soil Sci. Soc. Amer. Proc. 31: 223-226.

Power, J.F. 1974. Urea as a nitrogen fertilizer for the great plains grasslands. J. Range Manage. 27: 161-163.

Pulkinen, D.A. 1979. Potassium related soil fertility research on alfalfa forage production in northeast Saskatchewan. pp. 61-64. Proc. Workshop on K Related Soil Fertility Research in Western Canada, Potash and Phosphate Institute, Saskatoon, Sask.

Read, D.W.L. 1969. Residual effecrts from fertilizer on native range in southwestern Saskatchewan. Can. J. Soil Sci. 49: 225-230.

Read, D.W.L. and Winkleman, G.E. 1982. Residual effects of nitrogen and phosphorus fertilizer on crested wheatgrass under semiarid conditions. Can. J. Plant Sci. 62: 415-425.

Robertson, J.A. 1979. Summary of K related soil fertility research at the University of Alberta. pp. 35-38. Proc. Workshop on K Related Soil Fertility Research in Western Canada, Potash and Phosphate Institute, Saskatoon, Sask.

Rowell, M.J. 1984. Efficiency of urea application on perennial pasture. pp. 292-306. Proc. 1984 Alberta Soil Science Meetings.

Rowles, C.A. 1938. Effects of fertilizers pn alfalfa yields on wooded soils of Saskatchewan and related investigations on Black, Degraded Black, and Gray soils. M.Sc. Thesis, Dept. Soil Sci., Univ. of Saskatchewan, Saskatoon, Sask.

Sadler, J.M. and Stewart, J.W.B. 1974. Residual fertilizer phosphorus in western Canada: a review. Publ. No. R136, Saskatchewan Institute of Pedology, Univ. of Saskatchewan, Saskatoon, Sask.

Saskatchewan Agriculture and Food. 1989. Saskatchewan Agricultural Statistics Handbook 1989. Pub. Saskatchewan Agriculture and Food, Statistics Section, Regina, Sask.

Saskatchewan Agriculture. 1987. Guide to Farm Practice. Saskatchewan Agriculture and University of Saskatchewan, Saskatoon, Sask.

Saskatchewan Institute of Pedology. 1970-1977. Annual Soil-Plant Nutrient Research Reports. Dept. Soil Science, Univ. of Saskatchewan, Saskatoon, Sask.

Shalin, E. 1948. Fertilizers on alfalfa. M. Sc. Thesis, Dept. Soil Sci., Univ. of Saskatchewan, Saskatoon, Sask.

Simons, R.G., Grant, C.A., and Bailey, L.D. 1991. Response of alfalfa to placement of phosphorus and potassium. pp. 88-90. Proc. 1991 Man. Soil Sci. Workshop.

Smith, A.D. and Lutwick, L.E. 1975. Effects of N fertilizer on total-N and $NO_3$-N content of six grass species. Can. J. Plant Sci. 55: 573-577.

Smith, A.D., Johnston, A., Lutwick, L.E., and Smoliak, S. 1967. Fertilizer response of fescue grassland vegetation. Can. J. Soil Sci. 48: 125-132.

Smoliak, S and Janzen, H.H. 1988. Native range fertilizer guide. Alberta Agriculture Agri-Fax. Agdex 130/541.

Thompson, C.R., Dodds, D.L., and Hoag, B.K. 1987. Potash and phosphate fertilization on irrigated alfalfa. N. Dakota Farm Res. 44(6): 29-31.

Thompson, D.J. and Clark, K.W. 1989. Influence of nitrogen fertilization and mechanical stubble removal on seed production of Kentucky bluegrass in Manitoba. Can. J. Plant Sci. 69: 939-943.

Toogood, J.A. 1972. Effects of fertilizers, species, and maturity on yields, economic returns, and nutritive value of grasses and legumes grown on a Gray wooded soil. Can. J. Soil Sci. 52: 245-252.

Ukrainetz, H. 1969. Forage crop fertilization, eastern prairies. pp. 189-221. Proc. Canadian Forage Crops Symposium, Western Cooperative Fertilizers Ltd., Calgary, Alta.

Ukrainetz, H. 1974. Effect of fertilizer on bromegrass forage yield and quality. pp. 123-131. Proc. 1974 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.

Ukrainetz, H. 1979. Sulphur deficiencies. pp. 18-33. Proc. 1979 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.

Ukrainetz, H. 1982. Effect of two nitrogen sources on bromegrass production and soil pH. pp. 242-258. Proc. 1982 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.

Ukrainetz, H. and Campbell, C.A. 1988. N and P fertilization of bromegrass in the dark brown soil zone of Saskatchewan. Can. J. Plant Sci. 68: 457-470.

Ukrainetz, H., Campbell, C.A., Leyshon, A.J., and Zentner, R.P. 1985. Feasibility of applying fertilizers to forage grasses during winter in Saskatchewan. pp. 144-162. Proc. 1985 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.

Ukrainetz, H., Campbell, C.A., Zentner, R.P., and Monreal, C. 1988. Response of bromegrass to N, P, and S fertilizer on a gray luvisolic soil in northwestern Saskatchewan. Can. J. Plant Sci. 68: 687-703.

Walker, D.R. and Bentley, C.F. 1961. Sulphur fractions of legumes as indicators of sulphur deficiency. Can. J. Soil Sci. 41: 164-168.

Walker, D.R. and Doornenbal, G. 1972. Soil sulfate II. As an index of the sulfur available to legumes. Can. J. Soil Sci. 52: 261-266.

Wright, M.J. and Davison, K.L. 1964. Nitrate accumulation and nitrate poisoning in animals. Adv. Agron. 16: 197-247.

Wyatt, F.A. 1931. Residual effect of fertilizers. Sci. Agric. 11: 387-396.

Zentner, R.P., Ukrainetz, H., and Campbell, C.A. 1989. The economics of fertilizing bromegrass in Saskatchewan. Can. J. Plant Sci. 69: 841-859.