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Soil Fertility in Dryland Agriculture

Essentially all of the dryland soils have supported the same cultivated crops, i.e., wheat, sorghum, and oil crops, since they were plowed out of prairie grasses. The ecology of the grass prairie provided a reserve of readily decomposable soil organic matter that supplied N for crops for a number of years. However, production of nonlegume crops combined with summer fallow (where the crop is grown once in two seasons) for maximum release of soil N and storage of soil water reduced this reserve supply of soil N. Present yields of most nonlegume crops grown every year depend on use of commercial fertilizers.

Sievers and Holtz (1922, 1926) identified the importance of an incubation period to release available N from soil organic matter during the summer fallow season. They estimated that in 39 years of cropping, mostly in a wheat–summer fallow system, silt loam soils of eastern Washington had lost 22% of the N and 34% of the humus.

Soil N and C losses have been large with cropping systems studied in Oklahoma. Soil organic matter losses on a Pratt fine sandy loam (Psammentic Haplustalf) at Woodward, Oklahoma, averaged 60% by 1957 (Haas and Evans, 1957). Organic matter losses were significantly faster in the Southern Great Plains than in northern regions because of higher temperatures. This loss in soil organic matter has resulted in increased dependence

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on fertilizer to supply the crop N requirement. The deep prairie soil (Kirkland silt loam Udertic Paleustoll) at Stillwater, Oklahoma, supplied enough native soil N to produce about 1344 kg of wheat/ha, or approximately 45 kg of N ha^{-1} y^{-1} for more than 86 years. Fallow and row crop farming accelerated the loss of soil N and C when compared with continuous cropping (Haas and Evans, 1957).

Pittman (1977) found that six of seven nonfertilized dryland crop rotations in southern Alberta, including combinations of fallow, wheat, alfalfa, and grass had depleted several major plant nutrients in the soil within 20 years. Average contents of organic matter, total N, and exchangeable K were decreased by 14.5, 10.1, and 26.7%, respectively, in the 0- to 15-cm soil depth and by 24.1, 13.3, and 25.7%, respectively, in the 15- to 37-cm depth. Total P content of the soil changed little during 20 years of cropping.

In general, soil organic matter content is highest in the eastern part of the Northern Great Plains area and decreases from east to west. Soil test summaries show that these soils are inherently low in available soil P and high in available K (Bauer et al., 1966; Ward and Carson, 1975). Therefore, yield responses to P fertilization are common but not to K. Nitrogen fertilizer requirements vary with the amount of N mineralized from the time of crop removal until the time the next crop is seeded and with the yield potential of the seeded crop under the prevailing moisture conditions.

In the semiarid Northern Great Plains, water, available soil N, and P often limit plant growth. In addition, soil temperatures are frequently below optimum during the early growth stages, and ambient air temperatures are above optimum during heading and ripening stages.

A summary of long-term cropping studies in the Pacific Northwest shows (Horner et al., 1960) that soil organic matter ranged from 3 to 4% in the Pullman, Washington area (about 500 mm of rainfall), 2.0% at Pendleton, Oregon (about 350 mm of rainfall), and 1.3% at Lind, Washington (about 200 mm of rainfall) when experiments were started in the 1920's. Marked decreases have been observed in all areas since that time. Two major factors were responsible for the rapid decrease in soil organic matter: (i) limited return of crop residues with little or no addition of N to the fallow system and (ii) loss of topsoil by soil erosion from both wind and water during the summer fallow period.

Most of the soils in Washington, Oregon, and adjacent dryland areas of Idaho had adequate levels of available soil P to supply crop needs when cropping started. The prairie wheat-producing areas of Canada and associated soils along the Canadian-U.S. border that are largely glacial till soils and inherently low in available P were some of the first soils to show response to applied P. Erosion of hilltops has resulted in both P and K deficiencies.

Soils of the Southern Great Plains vary markedly in their capacity to supply crops with adequate P; some soils have adequate supplies of P, whereas others have extremely low supplies. There seems to be little relationship between the type of cropping system and P availability. However, soil erosion has played an important role in reduced P availability.

This chapter discusses soil associations specifically related to nutrient availability and fertilizer response. The major soil associations throughout the dryland area and the relationships between chemical and physical characteristics, as well as environmental and management practices, are outlined in Chapter 1.

21-1 NUTRIENT DEFICIENCIES IN CALCAREOUS SOILS

Calcareous soils generally have apatite compounds, and dicalcium phosphate ($CaHPO_4$) and tricalcium phosphate [$Ca_3(PO_4)_2$] are the major inorganic P components (Olsen, 1953; Seats and Stanberry, 1963). As levels of organic P have diminished with cropping, P deficiency has become more widespread. The alkaline pH of calcareous soils favors the dominance of 2:1 type clay minerals (Grim, 1953). Low leaching losses of K have contributed to high soil K levels and to K fixation when hydrous mica minerals are present.

The carbonate chemistry of soil systems and soil pH influence the availability of cations as well as P. The influence of soil pH, CO_2, carbonates, and P compounds on solubility of $H_2PO_4^-$ is discussed by Lindsay and Moreno (1960). The solubility of $H_2PO_4^-$ or HPO_4^{2-} in soils is a complex system. Calcium carbonate, CO_2, and soil pH are the critical factors controlling P in soil solution in neutral to alkaline soils. The effect of calcareous soil systems on plant availability of soil P has been reviewed (Grunes, 1959; Seats and Stanberry, 1963; Miller, 1974).

An understanding of the reactions taking place when water-soluble P fertilizers are added to these soils is important. The $H_2PO_4^-$ ion reacts with Ca^{2+} to form dicalcium phosphate ($CaHPO_4$), which has a solubility of 0.2 g/L. As these ions react in a calcareous soil, the contact with particles of lime ($CaCO_3$) result in formation of tricalcium phosphate [$Ca_3(PO_4)_2$], which can become a surface coating on limestone granules. An equilibrium exists between the limited amounts of $H_2PO_4^-$ and HPO_4^{2-} ions in the soil solution and these less soluble P compounds. Thus, in fertilizer management, practices that either minimize intimate contact between P fertilizers added and limestone particles present in these soils or that place P fertilizer in intimate contact with acid-forming materials, e.g., ammonium sulfate [$(NH_4)_2SO_4$], increase the solubilization of compounds formed.

Potassium deficiencies are being identified on eroded hilltops in the Pacific Northwest and on sandy soils in the Northern and Southern Great Plains. The widespread occurrence of hydrous mica minerals (Grim, 1953) throughout these areas has ensured a relatively high reserve of slowly available soil K.

The solubility of heavy metal micronutrients generally decreases as soil pH increases, and higher pH vlaues are more prevalent where erosion or land leveling has exposed calcareous subsoils. Zinc, Mn, and Fe deficiencies can be expected on crops that are susceptible to deficiencies of these nutrients. Fortunately, wheat and barley, two of the most widespread crops produced under dryland conditions, are either efficient at taking up these nutrients from calcareous soils or have low requirements. Deficiencies are seldom found in these crops.

Deficiencies of Zn and Fe are more frequently encountered on sorghum, corn and flax crops in the Great Plains. Practices followed to identify and correct these problems will be discussed in later sections of this chapter.

Sulfur deficiency is widespread throughout the Pacific Northwest, isolated areas of the Great Plains, and western prairie provinces of Canada, principally on noncalcareous soils where gypsum ($CaSO_4 \bullet 2H_2O$) is not present in subsoils. This deficiency was seldom a problem in earlier production of cultivated crops in these areas because breakdown of soil organic matter during a summer fallow season supplied enough S for crop requirements. All of these practices increase the S requirement of the cropping system. The widespread use of commercial N with increased yields and increased incorporation of crop residue to help control erosion has started to increase equilibrium soil organic matter levels (Horner et al., 1960) and has thus increased total S needs. In the Pacific Northwest, these effects have been combined with the production of legumes, which have higher S requirements, and a return to annual cropping or cropping 2 out of 3 years to wheat and barley in many areas. Thus, where $(NH_4)_2SO_4$ or other S-carrying fertilizers have not been used, S deficiency has become a more common occurrence (Leggett et al., 1959; Ramig et al., 1975).

21-2 NUTRIENT DEFICIENCIES IN ACID SOILS

Some dryland soils in the western states are moderately acid, and some have acidic A horizons with alkaline B and C horizons. Acid soils are found around the foothills of the mountains in the Pacific Northwest, some Rocky Mountain areas, Turtle Mountains in North Dakota, and higher rainfall areas in Oklahoma, Texas, and Kansas. The rainfall is high enough, especially when combined with lower evapotranspiration rates at higher elevations, to support a stand of timber. Increased use of ammonium fertilizers in the last 30 years has also contributed to soil acidity in these areas.

Similar areas can be found in Alberta where environmental conditions resulted in the development of moderately acid soils. However, a review of literature has indicated that soil acidity has probably not been severe enough to result in Al toxicities in these areas. Application of lime on soil with pH values below 5.0 has resulted in increased wheat yields in Oklahoma and the Pacific Northwest states.

Sulfur deficiency is more widespread on these moderately acid soils, probably because of greater leaching potential. Molybdenum deficiencies have been identified on legumes (Reisenauer, 1956) on moderately acid soils in the Pacific Northwest and may be more widespread on land cleared of trees.

21-3 IDENTIFYING NUTRIENT DEFICIENCIES

Researchers, extension workers, and farmers generally rely on three methods to identify nutrient deficiencies and to predict the need for fertilizers. The two most widespread are (i) visual observation of response to fertilizer applications and (ii) the identification of specific visual deficiency symptoms. The search for more dependable methods of recommending specific rates of fertilizer has led to the development of a third method—chemical analyses of both soil and plant samples to identify nutrient deficiencies and predict plant response to fertilizers quantitatively. An extensive review of assumptions underlying use of soil and plant analyses and methods employed throughout the USA has been edited by Walsh and Beaton (1973).

21-3.1 Use of Soil Analyses to Predict Fertilizer Response

The use of soil analyses to predict plant response to fertilizer is based on a correlation between some fraction of a nutrient extracted from a representative soil sample and a measured response from fertilizer application. Soil analyses-fertilizer response relationships, except for NO_3-N, are generally based on an analysis of "plow layer" soil samples. This procedure has generally given a reliable basis for predicting response where adequate and up-to-date field calibration data are available. Levels of available P, K, and micronutrients are generally lower in subsoil horizons than in the "plow layer"; therefore, chemical analyses of surface soil samples provide a measure of these nutrients that can be related to crop response. A notable exception to this rule has been in the wheat-growing areas of Utah (Neilson and Lamborn, 1970; Lamborn, 1970) where buried profiles sometimes contain more available P than surface soils.

21-3.1.1 Nitrogen Soil Analysis

Dahnke and Vasey (1973) have reviewed some of the important problems associated with use of different N soil test procedures. Recent studies have emphasized that NO_3-N in the surface 1.2 m of soil is more important than the NO_3-N in the soil below a depth of 1.5 m. Soil testing laboratories in the Great Plains are using NO_3-N soil analysis to measure carryover or residual and mineralized N. These laboratories recommend soil sampling to a minimum of 60 cm, with samples to 1.2 m preferred where plants have unrestricted rooting to this depth.

Leggett (1959) emphasized that the N required for anticipated optimum yield was supplied by (i) NO_3-N present in the root zone at planting, (ii) N that should be released from soil organic matter during the spring of the year, and (iii) commercial N to be added. A reasonably accurate measure of the NO_3-N in the root zone can be made at planting. The amount of N released from soil organic matter during the spring of the year for a specific soil and environmental condition is reasonably constant. Major errors in these predictions are associated with the marked fluctuation in yield potential caused by variation in environmental conditions between years. Summer fallowing usually ensures that the soil water profile is near field capacity to a depth of 120 cm by the start of the growing season, but rainfall during the 3 or 4 months preceding crop maturity and temperature, especially 4 weeks before crop maturity, can combine to cause wide fluctuations in yields from year to year. Nitrogen removed by livestock grazing small grain crops in the Southern Great Plains can have a marked effect on crop nutrient requirements. This practice will be discussed in latter sections of this chapter.

Yield increases from fertilizer applications are not always assured. In dryland farming regions in the Great Plains and west, available soil water varies and often limits yields. Therefore, yields fluctuate widely. Growers are faced with the problem of deciding on realistic yield goals for specific soil conditions that are most profitable over a period of years.

21-3.1.2 Phosphorus Soil Analysis

Soil P solubility on neutral and alkaline pH soils is controlled by the formation of $CaHPO_4$ and $Ca_3(PO_4)_2$ as previously discussed. The sodium bicarbonate procedure to extract P from calcareous soils, developed by Olsen et al. (1954), is in widespread use (Thomas and Peaslee, 1973).

The sodium bicarbonate extract has been used to predict P response on moderately acid soils in western Oregon (Jackson et al., 1964), indicating a wide range of adaptation for this extracting procedure if adequate field calibration data are available.

The Bray-1 weak acid extract is used (Halvorson, 1970) to measure soil P in western Oregon and in acid soils of northern Idaho. Oklahoma and Kansas have used the Bray-1 weak acid with soil solution ratio (up to 1 to 100) to extract P on acid and calcareous soils. This increased amount of extracting solution ensures that a moderate amount of carbonate in a soil system will not neutralize the acid-extracting solution. The range of extracting solutions used to measure some fraction of "plant available P" emphasizes that different extraction procedures can be used on many soils *if good field calibration data are available* and if different critical levels are established for different environmental conditions.

The question of P levels in subsoils should be established for different soil formations since it is generally assumed that subsoil levels of plant available P are low where surface soils are deficient. Lamborn (1970) found this was a factor affecting calibration of P soil tests in Utah.

21-3.1.3 Potassium Soil Analysis

Plant response to application of K has been limited in dryland agricultural production in the western U.S. Removal of K by dryland crops has been relatively low. However, responses to K fertilization have been measured under some conditions. Differences in clay content and types of minerals present in soils can affect established critical K soil test values because these soil properties affect the reserve K supply.

Ammonium acetate has been used extensively to extract cations and is a suitable solution for use in analytical flame instruments, because the NH_3 and acetate volatilize with heat; thus, salt problems on burners are minimized. The NH_4 ion, however, tends to "trap" K ions in nonexpanding hydrous mica minerals and does not provide a good measure of slowly available or "reserve" K.

Good characterization of "plant-available" and "reserve" soil K plus a quantitative identification of the hydrous mica component of clay minerals will be an important part of future soil chemistry studies where K response becomes more widespread.

Doll and Lucas (1973) have pointed out that good correlations have been obtained between some measure of exchangeable K, crop response, and K removed by crops where adequate field calibration data have been available.

21-3.1.4 Sulfur Soil Analysis

Response from S fertilization has generally been limited to legumes or annual cropping in higher rainfall areas. Use of soil analyses to predict S response presents problems comparable with the use of NO_3-N soil analyses (Reisenauer et al., 1973). Sulfur is released from soil organic matter during incubation periods that favor microbiological activity, with oxidation producing SO_4-S that is subject to leaching from most soils. Quantitative chemical problems associated with measuring low SO_4-S levels has limited use of S soil tests to predict S response.

Plant analyses for S offers one technique for evaluating S fertilizer programs (Pumphrey and Moore, 1965b); however, critical S levels vary with crop maturity so that sampling procedures must be specifically defined. Nitrogen/sulfur ratios offer a possible solution to this problem (Pumphrey and Moore, 1965a) because both N and S decrease with crop maturity. An N/S ratio wider than about 16:1 in forage and grain crops has been suggested as an indication of S deficiency.

21-3.1.5 Micronutrient Soil Analysis

Heavy metal micronutrient deficiencies occur most often on irrigated soils where leveling for surface irrigation has exposed calcareous subsoils and where corn, potato, bean, and other crops are produced that are more susceptible to Zn, Mn, and Fe deficiency.

Chelate-extracting solutions developed by Lindsay and Norvell (1978) have more widespread use than other extractants for heavy metal micronutrients (Viets and Lindsay, 1973).

Boron deficiency can be a problem in dryland legume production but is seldom observed for wheat, barley, or grass crops. Boron deficiency is often associated with a deficiency of growing season rainfall because low soil water limits B availability (Tisdale and Nelson, 1975); thus, B deficiency on alfalfa varies considerably from year to year. The hot water extraction method of Berger and Truog (1939) is often used to assess soil B. However, because a large number of factors (soil pH, soil water, soil organic matter, clay minerals, and soil texture) affect B availability, relationships between B soil tests and response to B application are difficult to establish.

21-3.2 Use of Plant Analyses

Chemical analyses of plant samples provide a basis for quantitative evaluation of deficiencies, toxicities, imbalances, and other crop production problems. Plant part sampled (i.e., leaf vs. stem), stage of maturity, proper sample handling, possible sources of contamination, and other factors can affect the level of nutrients found in the plant; failure to consider these factors has sometimes resulted in misuse of this tool to diagnose soil fertility-plant nutrition problems.

The use of plant analyses as a basis for predicting fertilizer needs in dryland agriculture has limitations. Many times fertilizers should be applied at or before planting if special application methods, like banding, are required for optimum fertilizer use efficiency. Since a specific growth stage must be achieved before a proper plant sample can be taken, it is often too late to get full benefit of fertilizer applied at this late growth stage. Phosphorus and cations that are not easily moved with rainfall into the root feeding zone should almost always be applied at or before planting for efficient uptake. Thus, for these nutrients, plant analyses for dryland agricultural production becomes more of a postmortem and a method to assess current year's fertilizer program before the next crop is planted.

Limited progress has been made in establishing critical nutrient levels for small grains because of problems in using plant analyses information for adjusting current fertilizer needs. Brown and Jones (1977) reported that plant samples must be taken at very early stages of growth (probably the 3 to 4 leaf stage) to obtain a reliable estimate of N needed for winter wheat in irrigated areas of southern Idaho. Unpublished data by the senior author suggests that leaf samples should be taken during tillering to evaluate the P status of winter wheat under western Oregon growing conditions. Other researchers have emphasized the need for plant sampling during tillering in assessing the P nutrition of winter wheat in Oklahoma (Baker and Tucker, 1973). Leaf samples taken at later growth stages have limited diagnostic value.

21-4 NUTRIENT REQUIREMENTS BY DIFFERENT CROPS AND CROPPING SYSTEMS

In general, as the level of plant available soil water increases, the yield response to added fertilizers increases. Thus, the yield potential from available water, stored in the soil or expected as rainfall, and the amount of plant available N required to achieve that yield become the two most critical factors in balancing fertilizer requirements.

The influence of stored soil water at seeding and growing season precipitation on the response of spring wheat to N and P fertilization is shown in Tables 21-1 and 21-2 (Snider et al., 1968). Because yield responses to fertilization are governed by available water, most of the states in the Great Plains and Canadian provinces consider the amount of available water

Table 21-1. Effect of amount of stored soil water at seeding and growing season rainfall on spring wheat yields and yield responses to N fertilizer on nonfallowed soils, North Dakota (Snider et al., 1968).

Stored water†	Rainfall‡	Number of trials	Yield of check	Yield response to added N (kg of N/ha)§ 22	45	67
cm			kg/ha			
Less than 5	Less than 15	5	640¶	150	130	190
	15 to 20	11	1110	170	120	100
	More than 20	10	1360	320	370	310
		26	1040	220	220	200
5 to 10	Less than 15	9	1270	190	270	250
	15 to 20	5	1450	380	540	620
	More than 20	6	1870	300	540	420
		20	1490	290	420	390
More than 10	Less than 15	2	1610	350	390	230
	15 to 20	5	1590	450	790	1040
	More than 20	13	1700	560	870	940
		20	1660	520	800	890

† To 120-cm depth or dry zone above 120 cm.

‡ From seeding to 5 days before harvest. Less than 15 cm is below average rainfall during the spring wheat growing season in North Dakota; 15 to 20 cm from slightly below to average; more than 20 cm from average to above average.

§ A constant rate of P (0–46–0) was applied by drill attachment.

¶ Figures rounded from original publication.

Table 21-2. Effect of amount of stored soil water and growing season rainfall on spring wheat yields and yield responses to P fertilizer in fallowed soils of "very low" P test level, North Dakota (Snider et al., 1968).

Stored water†	Rainfall‡	Number of trials	Yield of check	Yield response to added P (kg of P/ha)§ 7	22	17	22
cm			kg/ha				
Less than 5	Less than 15	1	280	50	70	110	140
	15 to 20	2	1140	280	280	290	300
	More than 20	2	1130	350	470	340	380
		5	960	260	330	270	300
5 to 10	Less than 15	5	1270	120	190	210	210
	15 to 20	3	1940	390	400	420	400
	More than 20	3	1860	540	790	840	840
		11	1610	310	410	440	440
More than 10	Less than 15	5	1610	340	430	500	550
	15 to 20	8	2220	440	550	620	660
	More than 20	4	2110	560	790	830	810
		17	1940	440	570	630	670

† To 120-cm depth or dry zone above 120 cm.

‡ From seeding to 5 days before harvest. Less than 15 cm is below average rainfall during the spring wheat growing season; 15 to 20 cm from slightly below to average; more than 20 cm from average to above average.

§ Phosphorus (0–46–0) was applied by drill with the seed.

when making fertilizer recommendations. In North Dakota, fertilizer recommendations are based not only on soil test data obtained in the laboratory but also on stored-soil water at seeding time, crop to be grown, and indirectly, on probable growing season rainfall and yield potential (Wagner and Vasey, 1970). In Saskatchewan, generalized N and P fertilizer recommendations are made for each soil zone (e.g., Brown, Dark Brown Soils), soil texture, and crop species based on long-term average yield data (Saskatchewan Advisory Council on Soils, 1977).

21-4.1 Wheat and Other Small Grains

Wheat is grown on more acres than any other crop in the dryland areas of the western USA and Canada. Approximately 16 million ha are devoted to wheat production in the dryland area of the USA. In the prairie provinces of Canada over 9 million ha of wheat are grown. Barley is an important crop in the western states with more than 0.5 million ha seeded each year. Oat and rye are grown for both grain and forage, but hectarages have declined in recent years.

Wheat yields have increased substantially during the last 20 years, and it is no coincidence that yields have increased simultaneously with increased fertilization of that crop.

Most of the early fertilizer experiments on wheat in the Great Plains showed that P was the most limiting nutrient. Yield increases from P fertilizers were reported from several locations (Bauer et al., 1966; Eck et al., 1957; Harvey et al., 1961; Power et al., 1961; Russel et al., 1958). With continued cropping, N soon became limiting, and N deficiency symptoms were widespread. Now, N fertilizer is applied to a majority of the dryland wheat fields.

Wheat requires approximately 30 kg of available soil N for each 1000 kg of grain produced up to a yield of about 2200 kg/ha, or to the point where the yield curve starts to level off. Above that, slightly more N is required to produce a unit of grain because of decreased N efficiency. Balancing N requirements with available water has been discussed in section 21-3.1.1.

In the Southern Great Plains, much of the winter wheat is grazed by cattle in the fall and winter. Grazing removes N, and additional N must be supplied if wheat is harvested for both forage and grain. Each 1800 kg of dry weight of small grain forage produced requires about 36 kg of N (Tucker, 1977). The amount of wheat forage potential depends on many factors, including soil water, temperatures, and seeding dates. Grazing yields of 800 to 1600 kg of forage/ha are common for the fall and winter, and grazing can continue until the jointing stage of growth without seriously affecting grain yields (Staten and Heller, 1949).

The N requirements of other small grains (barley, oat, ,and rye) are nearly identical to wheat on a kilogram of grain basis (Johnson and Tucker, 1979; Table 21-3). Growers should recognize that barley and oat are much

Table 21-3. Nitrogen requirements for small grain and oilseed crops being used in North and South Dakota to make N fertilizer recommendations (Wagner and Dahnke, 1977; Gelderman et al., 1977).

Crop	North Dakota	South Dakota
	g of N/kg of grain yield	
Winter wheat	--	40
Spring wheat	33–47	40
Feed barley	33–48	40
Malting barley	27-35	33
Oats	38–47	38
Rye	36-50	39
Flax	54	54
Safflower	40-53	50
Sunflower	50	50
Mustard	60	60
Rape	60	60

more susceptible to lodging with excess N than the commonly grown wheat cultivars. In addition, N rates on malting barley are usually about 30% lower to control protein levels and preserve malting quality.

Wheat is sensitive to low soil P levels. Most experiments show P fertilizer requirements for broadcast applications to be 40 to 60 kg of P/ha on extremely deficient soils, with lower rates or a "starter" application on soils testing moderately high.

Wheat and other small grain crops do not remove large amounts of soil K, and a large majority of soils used for wheat production in the West contain adequate exchangeable K. Responses of wheat to K fertilization can be substantial when soil P levels are low, but yield increases are generally lower than for forage and row crops. As with P, K fertilizer needs for small grains are determined by soil tests. Even with soil tests as low as 75 kg of exchangeable K/ha, 55 to 60 kg of K fertilizer will give maximum yields (Tucker, 1977).

21-4.2 Oil Crops

Oilseed crops occupy about 1.5 million ha of dryland soils in the Northern Great Plains and larger areas in the dryland areas of Canada, but only small hectarages in other dryland areas of western USA. The N requirements for flax, safflower, sunflower, mustard, and rape are reported in Table 21-3 (Bergman et al., 1975; Cobia and Zimmerman, 1975; Gelderman et al., 1977; Wagner and Dahnke, 1977). Mustard and rape generally require slightly more N than sunflower, safflower, or flax per kilogram of grain produced. Adams et al. (1978) reported that flax required 7 g of P and 40 g of K/kg of grain produced. In the Northern Great Plains, minor element deficiencies are not common in these crops. However, Moraghan (1978) reported that "chlorotic dieback" of flax results from a Zn deficiency. Addition of Zn corrected the nutritional problem. Although B deficiencies are rare, sunflower has a relatively high requirement; where B responses have been observed, 1 to 2 kg of B/ha has corrected the deficiency. Recommended rates of N, P, and K fertilizers vary with soil test levels and yield goals. Recommended rates of P and K for oilseed crops are similar to those recommended for small grain crops for similar soil test levels.

21-4.3 Grain Sorghum and Corn

Grain sorghum is grown extensively in the dryland areas of the Central and Southern Great Plains. Corn grown on dryland in the Northern Great Plains is used primarily for forage.

Nutrient requirements for grain sorghum are slightly less than for corn because of its more extensive fibrous root system and the lower grain-forage ratio for grain sorghum. The fertilizer needed for both crops depends on the soil's supply of each nutrient. The potential yield depends on the supply of N. Estimated N requirements range from 17.9 to 26.8 g of N/kg of grain or 33 g of N/kg of forage (Wagner and Dahnke, 1977). After a yield goal has been established, the preplant soil NO_3-N in the 60 cm soil profile can be subtracted from the total N requirement to determine fertilizer application.

Average yields of dryland sorghum and corn range from 3000 to 4000 kg/ha on most soils. Yield levels of 2000 to 3000 kg/ha are common in the drier regions where average annual precipitation is less than 500 mm. Nitrogen fertilizer rates commonly used vary from 18 to 60 kg/ha.

Rates of P on dryland grain sorghum and corn vary from 20 to 30 kg/ha on soils tested low in available P. Sorghum and corn respond to starter band applications of P especially if planted in cool soils (less than 10°C).

Sorghum and corn respond to K fertilizer on soils low in that nutrient. Lodging near maturity is often the first symptom of K deficiency on sorghum. The lodging may be a direct result of secondary disease resulting from low K levels. Whitney and Murphy (1974) showed the relationship between K rates, yield, and lodging on a K-deficient soil in Kansas. Practical K fertilizer levels for grain sorghum range from 20 to 70 kg K/ha on soils testing very low to moderately high K levels.

Most of the sorghum produced in the Southern Great Plains are grown on calcareous soils with resultant high pH values. Therefore, the availability of certain micronutrients may be restricted. Iron deficiency is common, with Zn deficiencies being reported (Thompson, 1969).

Soil-applied chelated Fe is effective in correcting Fe deficiencies, but rates required are sufficiently high to render them uneconomical. Sorghum seed coated with chelated Fe has been effective in reducing Fe deficiency, and foliar spraying various Fe compounds has also been effective. It is important to apply foliar sprays before the deficiency becomes too severe.

Zinc deficiencies in grain sorghum and corn have been observed in Kansas (Thompson, 1969) and Texas (Fenn, 1969) on high pH soils simultaneously having high soil P levels. Soil tests for Zn can be used to predict the need for Zn application. Zinc deficiencies can be corrected with the application of 3 to 8 kg of Zn/ha as $ZnSO_4$. Chelated Zn is available and lower rates can be used, but low rates of Zn need to be banded close to the seed to be effective (Bauer, 1968).

Some nutrient responses to S have been noted on grain sorghum in Texas, Nebraska, and Kansas (Tucker and Bennett, 1968). These responses have occurred on low organic matter coarse-textured soils. Sulfur requirements can be met by applying sulfate sources such as $CaSO_4$, K_2SO_4, and $(NH_4)_2SO_4$. Elemental S sources are effective if applied well ahead of planting. Where S is deficient, applying 30 to 40 kg of S/ha is generally sufficient.

21-4.4 Legumes

The principal legumes grown in the dryland areas are alfalfa and sweetclover. Some summer legumes are grown in the southern Plains, including mung bean, cowpea, guar, and Austrian winter pea.

Alfalfa production in the Southern and Central Great Plains has been variable throughout this century; plantings increase during periods of favorable rainfall and generally decrease with adverse climate and pest outbreaks. Also, the high quality of alfalfa hay has resulted in increased demands from the large cattle feedlots that have been established in the region. These increased demands for hay have also increased seed requirements and thus production of seed for new plantings.

Alfalfa generally removes more Ca, P, and K from the soil than most other field crops. Each metric ton of alfalfa hay will remove about 20 to 30 kg of N, 5 kg of P, 20 kg of K, 10 kg of Ca, 5 kg of Mg, and 5 kg of S.

Alfalfa yields are reduced from soil acidity; thus lime must be applied for optimum production to some acid soils along the eastern portions of the Southern Great Plains and few areas in eastern Washington and northern Idaho. Most states recommend application of lime when the soil pH is less than 6.2 to obtain good production and to ensure stand longevity.

Legume crops like alfalfa and sweetclover should obtain their N needs through rhizobium fixation of atmospheric N. Therefore, the major limiting nutrients for legume production are P, K, and S; Mo deficiency occurs on a small number of moderately acid soils. Small amounts of N are often applied at or just prior to seeding to help establish seedlings before the rhizobia actively supply N to the plant. Soils low in available P frequently require 75 to 100 kg of P/ha to maximize alfalfa yields (Tucker, 1977). Corresponding P needs for alfalfa production in the Northern Great Plains region would be about one-half those reported for the Southern Great Plains. Phosphorus fertilization is just as important in increasing alfalfa seed yields as hay yields on P-deficient soils.

Potassium removal by alfalfa cut for hay is large. Therefore, many fields with a history of high alfalfa yields are becoming deficient in K. Potassium fertilizer recommendations range from 200 to 250 kg of K/ha in the Southern Great Plains and 60 to 90 kg of K/ha in the Northern Great Plains on soils testing very low in K.

Both Zn and Fe deficiency symptoms have been identified on alfalfa in the Southern Great Plains, and even though the symptoms have been corrected by Zn and Fe applications, data are not available showing yield increases from these micronutrients.

The summer legumes, cowpea, mungbean, and guar, all have similar soil nutrient requirements, with P being the most limiting nutrient. Much smaller quantities of P are necessary to reach optimum yields than for alfalfa. Maximum yields of these crops have been obtained with the application of 40 to 80 kg of P/ha. Most Southern Great Plains soils contain adequate K for maximum yields unless these crops are harvested as hay over a period of time.

Legumes contribute to the N economy of the soil, leaving some residual N for subsequent crops. However, total N_2 fixation while the crop is growing can be higher than N left for subsequent crops. Some comparisons of annual N fixation and residual, or carryover, N show 220 and 90 kg N/ha for alfalfa, 110 and 45 kg of N/ha for cowpea, 90 and 25 kg of N/ha for mungbean, and 135 and 45 kg of N/ha for guar, respectively. Tucker et al. (1971) concluded that over 90 kg of N/ha was available to a wheat crop the first year after alfalfa, and 50 to 70 kg of N/ha was available for the second wheat crop. If wheat is planted after alfalfa, stubble mulching the alfalfa sod will reduce the N released the first year. The practice tends to distribute the N released over 2 years after the alfalfa crop, thus helping to avoid excessive vegetative growth the first year.

The economic value of using legumes to supply the N needs of crops in the Northern Great Plains is questionable with the current costs of commercial N fertilizers. Brown (1964) concluded that legumes contributed 34 to 45 kg of N/ha per year to following crops; however, residual N from the legume is not enough to meet N requirements of grain crops in a 3- and 4-year rotation. Therefore, supplemental N is needed for optimum crop production, especially when forage is removed as hay (Haas et al., 1976; Jensen and Weiser, 1971; Bauer and Zimmerman, 1975). The N contribution varies with the legume growing conditions. Reduced subsoil moisture rather than inadequate N supply is a serious problem that accompanies the growing of deep-rooted legumes in drier areas.

21-4.5 Grasses

There are approximately 72 million ha of rangeland in the Northern Great Plains. Nitrogen deficiency has been identified as an important limiting factor to herbage production on these rangelands (Lorenz and Rogler, 1973; Power, 1972; Rogler and Lorenz, 1969; Wight and Black, 1979). Power (1972) concluded that adding rates up to 540 kg of N/ha to grasslands saturates the capacity of the soil-plant system to immobilize N. The system can then be maintained in a N-saturated condition if

$$\text{Annual fertilizer additions} + \text{Mineralization}$$
$$= \text{Immobilization} + \text{Irreversible losses.}$$

Thus, N can be eliminated as a growth-limiting factor to provide grass production from the available water supply. Responses to P fertilization are obtained after N requirements have been satisfied (Lorenz and Rogler, 1973; Wight and Black, 1979). Rogler and Lorenz (1969) report a 72% increase in animal carrying capacity on fertilized pasture compared with an unfertilized pasture. For optimum production, 35 to 56 kg of N/ha is required annually as fertilizer to satisfy the needs of rangelands.

Grasses in the Great Plains area consist of both warm and cool season species. Native grasses account for the largest hectarage, but several thousand hectares of improved species and strains have been planted. Improved pastures respond more to fertilizer applications of N and P in many situations (Houston, 1957; Williamson et al., 1977; Ahring et al., 1973; Moser and Anderson, 1965). Native ranges and meadows receive very little fertilizer, although some N and P responses have been reported (Harper, 1957; Grable et al., 1965; Elwell and Daniel, 1953). Native ranges have low total production, and competition from less desirable species often limits the economic returns from fertilization. Inefficient utilization of forage by grazing animals also limits returns on many ranches. Palatability of grasses is frequently improved by N application.

Cool season grasses respond to P application more than summer-growing species. The amount of P needed to reach maximum yields, however, appears to be about the same for both cool and warm season species (Elder and Tucker, 1968).

One kilogram of N fertilizer per hectare will increase dry matter forage production 12 to 16 kg/ha on cool season grasses and 20 to 25 kg/ha on warm season forages. In both cases, with grazing steers, this quantity of forage can add 1 kg to a beef animal with average management. Therefore, 1 kg of added N is expected to produce 1 kg of beef within the responding range of the yield curve.

21-4.6 Cotton

Cotton is grown on 1 million ha of dryland in the Southern Great Plains. Soils on which cotton is grown in the Southern Great Plains are more often deficient in N than other plant nutrients (Tucker and Tucker, 1968). Because of the rather warm climate, soil organic matter content has been severely depleted through oxidation during years of cultivation.

An understanding of the effects of N on growth and fruiting behavior of cotton is essential for N fertilizer management. Cotton fruit is borne on a fruiting branch that originates at the leaf axil on the main stem or on a vegetative branch (Tharp, 1960). Because N does promote plant growth, it increases the number of fruiting sites and yield potential (Tucker and Tucker, 1968). However, the cotton plant remains in the vegetative stage whenever insect infestations or climatic conditions cause fruit abortion and whenever excessive N rates in the above situation create too large a stalk for proper insect and disease control. Excessive available soil N too late in the season often reduces the plant's ability to mature and causes indeterminate growth. Therefore, enough soil N must be present early in the season to produce sufficient fruiting sites for adequate yield, but excessive N must be avoided in case a period of fruit abortion occurs. Rather high rates of available soil N are needed during rapid fruiting, but best yields and grades of cotton are produced if soil N is depleted during the maturing period. This program of N management requires special skill and at best is difficult to accomplish.

Several schemes to accomplish the above have been devised, the most successful being soil NO_3-N analyses at planting coupled with monitoring plant NO_3-N in petioles during the growing season (Tucker, 1965). This plan is being employed in some irrigated areas and in higher rainfall belts. It is not extensively used for dryland cotton production in the Southern Great Plains, where the common practice is to apply all the N prior to planting. Effects of N on plant type and fruiting are usually favorable if N rates are not excessive.

Two bales (450 kg) of cotton/ha is a good yield for dryland conditions in the Southern Great Plains. A bale of cotton contains approximately 18 kg of N in the seed and burs (Tucker and Tucker, 1968) and represents about 60% of the N contained in the plant. The soil N required for a two-bale yield is about 60 kg of N/ha.

Phosphorus will increase yields on deficient soils and frequently increases earliness and maturity. Early fruit set and maturation reduces vegetative production. One bale of cotton removes about 5.2 kg of P (Jones and Bardsley, 1965). In many experiments, 85 to 100% of the maximum yield increases are obtained with 20 kg of P/ha on soils with relatively low P levels. Soils of the Southern Great Plains generally have adequate K for cotton production, and limited K fertilizer is recommended. However, some of the sandy upland soils in the 600 to 800 mm rainfall area have responded to K whenever soil test K drops below 250 kg/ha. With a moderately high soil test (200 to 250 kg of K/ha) only 15 to 30 kg K/ha is suggested. Higher amounts are suggested at lower soil test levels.

Zinc has been deficient on a few cotton fields in the southern Great Plains, and B deficiencies have been suspected on a limited number of soils. Researchers in the Texas Blacklands (McLean and Niles, 1968) demonstrated that excess P applications reduced Zn availability. Where Zn is deficient, broadcast applications of 6 to 8 kg of Zn/ha as $ZnSO_4$, or band applications of 2 to 4 kg of zinc chelate is recommended.

21-4.7 Summer Fallow Cropping Systems

The term "summer fallow" has traditionally described a system in which a crop is grown once in two seasons. Fallow has been widely practiced in the dryland wheat-growing regions of the western USA (USDA-ARS, 1974). The popularity of summer fallow in dry regions is primarily attributed to water conservation leading to increased stability of production. Other benefits include better weed control and increased mineralization of N with 60 to 100 kg of N/ha accumulation from microbial decomposition during the summer fallow period. Summer fallow hectarage has fluctuated widely during the past few decades because of government agricultural programs but in general has declined rapidly in recent years.

The great advantage for summer fallowing has been ascribed to increased N mineralization (Haas et al., 1976). However, increased N fertilizer use has diminished this advantage, and many soils do not supply adequate mineralizable N with summer fallowing to meet the crop needs. Nitrogen fertilization is based on established yield potential and levels of soil NO_3-N present to achieve projected yield. Need for other nutrients does not change materially because of fallowing, and nutrents are applied commensurate with soil test levels.

In general, P is the major limiting nutrient under summer fallow conditions in the Northern Great Plains (Bauer et al., 1966; Black, 1969). Increases in grain yield from N and P fertilization are generally greater for early and medium seeding dates than for late-seeded spring wheat. Therefore, N and P fertilization of early-seeded spring wheat increases grain yields and economic returns more than the same N and P fertilizer levels for late seeding (Black and Siddoway, 1977b; Saskatchewan Advisory Council on Soils, 1977).

Most crops in the Central and Southern Great Plains are grown in a continuous (one crop each year) cropping system, and the nutrient demands have generally been established under this system. Where crops are grown every year on a field, the length of the fallow period (or period between harvest and planting) and soil water determine quantity of N mineralized. For small grains, the fallow period occurs during the summer, which is warm and is the period of greatest rainfall, with optimum conditions for mineralization of nutrients. Indigenous soil N varies considerably in the Southern Great Plains, but on large hectarages only 20 to 40 kg of available N/ha is mineralized.

In the Pacific Northwest, the amount of additional N needed to reach optimum yields on fallowed soils varies with location and precipitation. Leggett et al. (1959) found that in areas with less than 250 mm of growing season rainfall, 20 to 40 kg of N/ha was needed; in areas of 250 to 380 mm of growing season rainfall, N needs were 30 to 60 kg/ha; and in areas of more than 380 mm of growing season rainfall, 60 to 80 kg of N/ha was needed. They concluded that S fertilization often resulted in vegetative responses, usually without increased grain yield, in wheat grown on fallowed land.

21-4.8 Flexible Cropping Systems

Under flexible cropping systems in the Northern Great Plains, the farmer assesses the available soil water and expected growing season precipitation at seeding time before deciding to either crop or summer fallow (Halvorson and Kresge, 1982). If the farmer decides to crop, a crop is selected that should yield well on the available water supply. Good weed control and crop rotation are essential under this system. Nitrogen is gener-

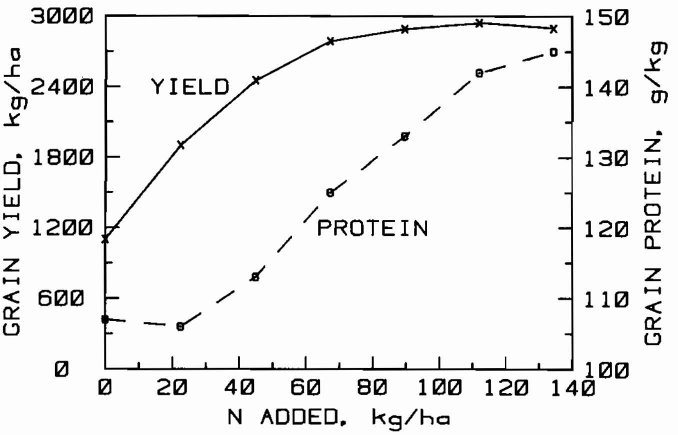

Fig. 21-1. Average grain yield and protein content of three winter wheat varieties (Winalta, Froid, and Centurk) (Halvorson et al., 1976).

ally the major limiting nutrient under a recrop situation. In the Northern Great Plains, approximately 34 kg of N/ha remains in 120 cm of the soil profile after a small grain crop (Black and Ford, 1976; Halvorson et al., 1976). Generally, N fertilizer needs to be added to attain maximum yields. A typical response of winter wheat to added N under recrop conditions is shown in Fig. 21-1 (Halvorson et al., 1976). Black and Siddoway (1976) found 34 kg/ha of additional fertilizer N generally provides adequate N for recrop conditions and near maximum yield. Crop rotation and chemical weed control are essential for maximizing returns on fertilizer dollars invested.

The P fertilizer requirements for crops grown on recrop land are essentially the same as for fallow conditions; an adequate soil P supply is necessary. Adequate P levels can be established either by broadcasting a relatively high rate of P to supply adequate P for several crops or by supplying each crop with the amount of P needed at seeding time. Recommended broadcast rates of P are approximately 1.5 to 2 times higher than rates recommended for banding with the seed.

Most N recommendations made for recropping in the Northern Great Plains are based on soil water available to the crop to be grown. Greater responses to fertilization are obtained as water supplies increase (Bauer et al., 1967; Russell et al., 1958). Larger supplies of soil water can be provided for crop growth by using snow management practices, such as tall wheatgrass barriers or standing stubble to trap winter snow (Black and Siddoway, 1976).

Because of the variable climate, especially rainfall, in the Central and Southern Great Plains, the most economical cropping systems over a period of time seem to be those that take advantage of soil water conditions at a given planting date (Harvey et al., 1961). These flexible cropping systems have been labeled as "opportunity rotations" (Luebs, 1962). Alfalfa is the most important legume used in cropping systems in the Southern Great Plains. Small grains do not yield well after alfalfa, but substantial yield increases have been reported for sorghum and cotton after alfalfa (Murphy and Tucker, 1969). Sweetclover, although productive in some years, is poorly adapted for use in short rotations. Cropping sequence studies in the Southern Great Plains have shown that all crops do well after cotton, provided soil water was replenished. Generally crops do poorly after grain sorghum.

Fertilizer requirements for crops in various cropping systems in the Southern Great Plains are computed on the same basis as in continuous monoculture with adjustments in the N fertilizer application being made for: (i) changes in yield goals, (ii) amounts and kinds of plant residues at seeding, and (iii) types of tillage during the fallow period.

In addition to N, S is often limiting during annual cropping in the Pacific Northwest. Application of S fertilizers will generally increase wheat yields under annual cropping provided that high levels of N fertilizer have been applied and no S has been applied in recent years.

Legumes in the crop sequence supply some N to subsequent crops and thereby reduce N fertilizer needs.

21-5 FERTILIZER AND WATER USE EFFICIENCY

The classic example of fertilizer increasing the efficiency with which water is used by plants is illustrated by response to N fertilizer. Assuming other nutrients are not limiting, we find that N can frequently double or triple the yield when adequate water, stored soil water, and growing season rainfall are available to grow a crop. Under most conditions, and unless affected by disease, insects, and other adversities, a crop will remove most of the available water from the rooting zone during a summer's growing season. Water in the surface 30 cm not used by the crop will probably be lost by evaporation during the hot, dry August weather in the Southern Great Plains and areas with extended summer drought.

Use of the summer fallow system of farming to store subsoil water, reduce weed problems, and increase the supply of available soil N in areas of Montana and the Dakotas has contributed to the development of saline seeps (Halvorson and Black, 1974; Doering and Sandoval, 1976a, b) on rolling topography as excess soil water has moved laterally to hillside seep areas. Systems are being developed to establish annual cropping that will use more of the potentially available water. Fertilizer and herbicides will be essential in replacing the traditional summer fallow system of farming.

21-6 FERTILIZER APPLICATION—SOURCE AND METHOD

Urea, $(NH_4)_2SO_4$, NH_4NO_3, anhydrous ammonia, solution 32, ammonium phosphates, and monocalcium phosphate (concentrated superphosphate) are the major sources of N, P, and N-P fertilizers used in this area of the USA. Low costs have increased the amount of urea and anhydrous ammonia applied in recent years. Anhydrous ammonia is used extensively on large farms in many wheat-producing areas and accounts for over 80% of the N used in the Southern Great Plains.

Ammonium sources of N have some special advantages and disadvantages for this area. The NH_4 ion is positively charged and is not subject to leaching until after biological oxidation to NO_3-N. Ammonium nitrogen can be applied as soil temperatures approach 10°C when biological activity is reduced; under low temperature (less than 10°C) conditions, these materials will stay in the NH_4 form until the next spring. Nitrification inhibitors can be applied with NH_4 sources of N to provide additional delays to the nitrification process. Ammonia volatilization from N fertilizers has been studied extensively in laboratory experiments, but difficulties in measuring NH_3 volatilization has limited the experiments conducted under field conditions. Fenn and Kissel (1973) devised a procedure for measuring NH_3 volatilization directly; using this technique, they found large losses of N from $(NH_4)_2SO_4$ when it was applied to the surface of a calcareous Houston Black Clay (Udic Pellustert). Losses from NH_4NO_3 were much smaller. In these studies, high N rates (140 and 280 kg of N/ha) were applied in single applicataions. Laboratory studies (Fenn and Kessel, 1975) showed losses from surface-applied $(NH_4)_2SO_4$-N to be substantially lower at low application rates. Surface applications of urea were inferior to other N sources in Oklahoma whenever single applications exceeded 90 kg of N/ha (Bohl, L. G. 1976. The effect of nitrogen sources, rates, and application methods on bermudagrass production. M.S. Thesis. Oklahoma State Univ., Stillwater). Losses ranged from 19 to 50% with rates of 550 kg of NH_4-N/ha. Nitrogen losses increased as soil temperatures increased.

The application of urea to perennial grass crops is of concern to agronomists. Field experiments in the Southern and Central Great Plains indicate volatilization losses of N from surface applications of urea to grass crops. Significant losses occur whenever: (i) the urea was applied to wet sods followed by no rain and rapid drying conditions (generally high temperatures, low humidity, and windy), (ii) application rates exceeded 90 kg of N/ha, and (iii) the sod was dense enough to intercept applied urea. Grazing or haying the forage prior to application helped reduce potential NH_3 losses. Also, burning destroys the urease enzyme and reduces these losses.

Urea and anhydrous ammonia are becoming more prominent N sources in the Northern Great Plains. Beaton (1978) forecast a significant reduction in production and consumption of dry NH_4NO_3 with considerable expansion in manufacture and sale of solid urea. Power (1974) points out that at high N rates, urea is generally 5 to 40% less effective than NH_4NO_3. He suggests that efficiency may not be as important as the fact that maximum yields obtained with urea may be less than with NH_4NO_3. Black and Siddoway (1977a) also found that urea was less effective than NH_4NO_3 when applied at rates above 45 kg of N/ha or applied in the late spring. In general, rates of N banded with the seed should not exceed 11 kg of N/ha in most Northern Great Plains areas (Black et al., 1980). The rate of N that results in salt or NH_3 toxicity varies with the source of N, soil pH, exchange capacity of the soil (clay and humus), soil water, and crop.

Chemical reactions take place as urea reacts with water in the soil. The initial hydrolyses forms ammonium carbonate or bicarbonate, which raises the pH in the area around a fertilizer granule. Thus, NH_3 can be released to the atmosphere; if urea is banded with the seed, the NH_3 released can reduce the stand of germinating seedlings (Black et al., 1980).

Problems resulting from banding NH_3-producing fertilizers are generally associated with placing the fertilizer near, or in contact with, the seed. Poor seedling emergence and subsequent root damage may result when fertilizers with high salt index are placed too close to the seed row under low soil water conditions. Seedling damage is accentuated when the soil has less than optimum water because salt concentrations increase with decreasing soil water. High rates or band applications of urea, $NH_4H_2PO_4$, and urea ammonium phosphate near the seed row may cause seedling damage from free NH_3, especially in dominantly neutral and calcareous soils of the Northern Great Plains. Pairintra (1973) found that damage to spring wheat seedlings from applications of various $(NH_4)_2PO_4$ fertilizers increased in the order ammonium polyphosphate < monoammonium phosphate < diammonium phosphate < urea ammonium phosphate. For each fertilizer, the damage was more severe with higher amounts of $CaCO_3$ in the soil.

As long as reasonable precautions are followed with special attention to local recommendations for time, source, and method of application, growers should expect efficient results from commercial N fertilizers.

Water-soluble P sources (monocalcium phosphate $[CaH_4(PO_4)_2]$ or ammonium phosphates) have advantages over $CaHPO_4$ or $Ca_3(PO_4)_2$, especially where the soil pH is neutral or above. The increased rate at which water-soluble P materials supply HPO_4 or H_2PO_4 to the soil solution has prompted their wide use in these areas. Phosphorus is relatively immobile in the soil. Therefore, all P materials should be applied at or before planting; they should either be banded with or near the seed, mixed with the seedbed, or plowed down.

Increased efficiency in use of P and most micronutrient fertilizers, when banded rather than mixed or broadcast, has been observed under a wide range of conditions (Ellington, 1978; Mortvedt, 1976; Richards, 1977), particularly in the Northern Great Plains where spring soil temperatures are often 5 to 15°C. As soil temperatures increase, the advantages from banding P decrease; in areas with higher soil temperatures, banding decreases P response (Baker et al., 1970). Also, as the P rate needed to alleviate deficiencies increases, differences in effectiveness between broadcast and band applications decreases. At very high rates (100 kg of P/ha), broadcast applications of P are just as effective as band placement (Ellington, 1978; A. L. Black, 1975. Unpublished data. USDA-ARS, Sidney, Mont.). Broadcast application requires less labor and time.

When using broadcast applications, Bauer and Kucera (1969) found that moldboard plowing incorporated P fertilizer to a deeper depth than a double disk or Noble blade. As minimum tillage and flexible systems become more prominent in the Northern Great Plains, placement for effective P fertilizer use becomes more important.

Mixing an acid-forming source of N, e.g., $(NH_4)_2SO_4$, with P fertilizers when banding with or near the seed on calcareous soils will increase the uptake of P and micronutrients (Miller, 1974; Jackson and Carter, 1976).

Sulfur is generally supplied as $(NH_4)_2SO_4$, 16–20–0 ammonium phosphate-sulfate, single superphosphate (10% S), K_2SO_4, $CaSO_4 \cdot 2H_2O$, and elemental S. All SO_4 sources are readily available for plant uptake and the SO_4 anion moves downward in the soil; thus, method of application is not critical. Elemental S must be finely ground so that oxidation to the plant available SO_4 ion will proceed at an adequate rate.

Micronutrients (Zn, Mn, and Cu) are generally applied as sulfates, with Fe applied as a chelate in most applications. Banding these nutrients with an acid-forming N fertilizer (Viets et al., 1957) can increase micronutrient uptake and is a practical way of getting soil applied Mn into a plant. Foliar application is an efficient method of applying most of these nutrients and is a practical way of correcting Fe deficiencies without lowering the pH of the soil system. Sorghum seed coated with chelated Fe, followed by foliar sprays whenever chlorosis appears, has been used to correct Fe deficiencies in the Southern Great Plains. High seeding rates have limited the use of Fe seed treatment with small grains.

Foliar application of chelated micronutrients reduces the risk of foliar burn, and uptake per unit of nutrient applied can be more efficient than with sulfate sources. These advantages help justify the higher cost per kilogram of nutrient applied for chelated materials. Generally, chelates of Zn, Mn, and Cu have limited advantage for soil application.

Application of B for dryland agriculture is generally limited to alfalfa and other legumes with high B requirements. Boron is almost always broadcast with some other material or applied as a foliar spray. Limited materials are on the market, thus water soluble B is generally used. Boron applications should not exceed 1.5 kg/ha annually in nonirrigated fields because the margin is small between deficiency from one crop and toxicity for a sensitive crop that might follow.

21-7 RESIDUAL CARRYOVER OF FERTILIZERS

Residual carryover of N, P, and S are the most important to evaluate because they have the largest impact on cost and plant growth. The carryover can be estimated by soil testing.

21-7.1 Measuring Residual or Naturally Occurring Levels of Nutrients

Chemical analysis of soil samples offers the best quantitative method of measuring residual carryover from fertilizer application and the naturally occurring levels of available nutrients. The measurement is an important aspect of managing different cropping systems. It becomes especially critical after drought periods, as in 1977, and periods of higher than normal rainfall, when N can be leached out of the root zone.

Carryover of excessive N from fertilization is probably minimal in dryland areas of the northern Great Plains because of the relatively low rates of N applied (less than 40 kg/ha) on intensively cropped lands and the even lower rates on summer fallowed land. Black and Halvorson (1976. Unpublished data. USDA-ARS, Sidney, Mont.) found that with the application of 34 and 67 kg of N/ha annually, residual N slightly accumulated in the 120- to 180-cm soil depth. The accumulation was greater for the 67 kg of N/ha treatment and under summer fallow system. Where safflower (a deep-rooted crop) was grown, the accumulation of residual N was negligible and in most cases no greater than in the area not receiving N fertilizer for at least 8 years. Under recrop conditions in the Northern Great Plains, 34 kg of N/ha is a common level of residual NO_3-N remaining to a depth of 120 cm after a small grain crop (Brown, 1964; Halvorson et al., 1976).

Residual P carry-over from P fertilization in the Northern Great Plains is detectable with the sodium bicarbonate soil test. Phosphorus carry-over work by Read et al. (1977) and Bailey et al. (1977) showed that a single large application of 100 kg of P/ha was effective over an 8-year period in increasing wheat and flax yields. Higher applications of 200 and 400 kg of P/ha were expected to be effective for several more years because of the higher level of extractable P remaining in the soil from these treatments. Even in the eighth year after application, yield increases were 11 to 60% greater than the check.

Tucker (1977) has observed marked carryover or buildup of both N and P in the Southern Great Plains. Use of P fertilizers has resulted in a marked reduction of P responses being observed in the field.

In a recent series of wheat experiments, Gardner et al. (1975) found significant accumulations of NO_3-N on wheat-producing farms in the Columbia Basin counties of Oregon.

21–7.2 Losses of Nutrients by Leaching

Leaching of nutrients is restricted to NO_3-N and SO_4-S, and these losses are probably restricted to summer fallow areas during periods of above normal rainfall.

Over 70% of the area in the Northern Great Plains is in grass. Under present management, Power (1970) concluded that the possibility of NO_3-N leaching through soils in grass is remote. In soils cropped annually to small grains, movement of NO_3-N has been generally restricted to the upper 2 m of soil. He concludes that NO_3-N could possibly move below the root zone in spring grains in a fallow rotation during the 21 continuous months the soil supports no growing crop.

Sulfur will be subject to leaching or accumulation in the subsoil whenever $(NH_4)_2SO_4$ is used as an N source, and an optimum N application results in applying 10 times or more S than the crop needs.

21–7.3 Adverse Effects From Excess Nutrients

Adverse effects from excess nutrients are generally limited to (i) naturally occurring concentrations, (ii) excess application of fertilizer, and (iii) accumulations of by-product contamination from industry.

Naturally occurring concentrations of B have been found in some areas of California and Oregon. Selenium has accumulated on shale soils in

Wyoming and the Dakotas. Excess Se is not a problem limiting plant growth, but can be a problem for animal health. Whereas Se can be toxic to animals in some areas of the Northern Great Plains, Se deficiency for livestock can be a problem in parts of the Pacific Northwest.

Some soils have naturally occurring accumulations of Mo and a soil pH >6.5 results in maximum availability of Mo. Molybdenum toxicity does not limit plant growth, but excess concentrations of Mo in animal diets can interfere with Cu utilization, especially in ruminants (Allaway, 1971, 1975).

Few instances of fertilizer applications have been high enough in dryland farming to result in toxic or adverse accumulations of nutrients.

21-8 EFFECTS OF EROSION ON SOIL FERTILITY AND NUTRIENT REQUIREMENTS

Soil erosion has caused a depletion of soil organic matter and loss of organic N and P in the surface 0 to 15 cm of soil. The "topsoil" also has higher concentrations of plant-available K under many prairie soils. Thus, reduced production on eroded hilltops can be caused from reduced availability of N, P, and K as much as from reduced storage of soil moisture. Reductions in soil fertility, as measured by losses in total N and organic C, have been greater under fallow than continuous cropping in the Northern Great Plains (USDA-ARS, 1974).

Eck et al. (1965) reported that many researchers have found that deficiencies of N, P, and K were primarily responsible for reduced yields where soils have eroded to the subsoils. On a Pullman silty clay loam (Torrertic Paleustoll) at Bushland, Texas, Eck et al. (1957) found that only N was required for maximum yield on the undisturbed soil, but both N and P were required when 10.16 cm or more of topsoil was removed.

The loss of A horizon and exposure of more calcareous horizons in subsoils presents another problem. The solubility, and thus plant availability, of Zn, Mn, and Fe is largely controlled by soil pH (Lindsay, 1972). As layers of $CaCO_3$, which accumulate under limited rainfall, and grassland prairies are exposed, the soil pH approaches 8.0 to 8.3. This high pH results in a marked reduction in availability of heavy metal micronutrients.

21-9 ENVIRONMENTAL IMPACT OF FERTILIZER

Nutrients from commercial fertilizer find their way into streams and groundwater as an environmental contaminant. Viets (1971a, b) has provided an excellent review of the different viewpoints surrounding this problem.

Most of the N and essentially all of the P, the two nutrients of greatest concern in water eutrophication, moves from cultivated farmland into streams by soil erosion. The use of commercial fertilizer has been an important factor in reducing soil erosion. Fertilizer has increased yields of both grain and crop residue. Proper management of crop residues during tillage is an important factor reducing soil erosion. Soil erosion is much more severe with summer fallowing or alternate year cropping than with annual cropping if residues are not left on the surface. Most erosion occurs during the winter after summer fallow, when crop residues have decomposed, and during early season growth, before crops provide ground cover. Commercial fertilizers, especially N, have been essential in the adoption of annual cropping in lower rainfall areas, thereby further reducing erosion.

Our present levels of crop production would require much larger hectarages if commercial fertilizer were not used. Farmers generally retire the steep lands, which are more costly to till and more subject to erosion than level land, as cultivated hectarages have been reduced. Expansion of cultivated hectarage to meet present levels of crop production would thus require cultivation of many hectares subject to more serious erosion than much of our present farmland.

Viets (1971a, b) has concluded that the overall impact of using commercial fertilizer has been to reduce environmental contamination. The impact is greater in dryland areas where yields are lower than with irrigation, and fertilizer is used in smaller quantities.

21-10 EFFECTS OF FERTILIZERS ON CROP QUALITY

The application of fertilizers can have important effects on quality of the crop produced. Quality is important for both human and animal nutrition.

One of the most obvious effects of fertilizers on crop quality is that of N fertilization on protein content of grain (Olson and Koehler, 1968). McGuire et al. (1974) found that fertilization not only increased yield and protein content of wheat, but also resulted in improved baking qualities, namely larger loaf volume, higher grain and texture scores, and greater dough stability. The first increments of added N generally give the largest yield increase with limited protein increase per unit of N. As the yield increase per unit of applied N decreases, the increase in protein per unit of applied N increases. These trends will vary somewhat with different wheat cultivars.

Nitrogen fertilization can be a critical factor in maintaining protein content of hard red winter wheats above 13%, the point where protein premiums frequently start. Millers can blend lower protein bread wheats with higher protein bread wheats to maintain the minimum desirable gluten strength for bread flour (Finney and Yamazaki, 1967).

The desirability of high protein for bread wheat is in contrast with medium to low protein content of soft white wheats from the Pacific Northwest. This wheat is used for pastry flour (7 to 8% protein) and exported to Asia for noodle flour (9 to 10% protein). Rainfall and temperature can have a marked effect on wheat quality in the Pacific Northwest. A soft white club wheat used for pastry flour fertilized for a yield potential of 4 t/ha in the Palouse area can have this yield potential decreased 20 to 30% in dry years with about the same amount of protein produced per hectare. This decrease can eliminate this class of wheat from the pastry trade but makes the wheat a desirable product for livestock feed.

Protein content is most frequently the factor limiting the quality of livestock feed. The addition of N fertilizers to grain crops for livestock not only increases both the grain yield and protein content, but generally increases the nutritional value of the grain. Similar effects are noted when forage grasses are fertilized with N for livestock pasture, silage, and hay. Literature showing possible effects of P fertilization on increasing the feed value of hay for livestock has been reviewed by Reid and Jung (1974). Legume hay, especially alfalfa, generally has a wide Ca/P ratio (often 10:1) while dairy cows require a Ca/P ratio of about 4:1 for optimum milk production. This ratio can be balanced by feeding grain with higher P contents and by adding inorganic P supplements to the diet. Thus, a frequently heard statement is that P fertilizer should be applied only to increase the yield of forage crops and not to influence nutritional value. However, recent work in Australia (Ozanne and Howes, 1970, 1971; Ozanne et al., 1976) has suggested that the P concentrations of subterranean clover (*Trifolium subterraneum* L.) required for maximum digestibility, especially as clovers start to mature, is higher than P required for optimum yield. Reduced digestibility was not corrected by supplementing the diet with inorganic P supplements in these studies. This question needs further investigation.

Bauer and Vasey (1964) found that K fertilization improved the quality of malting barley by increasing the percent of plump kernels, decreasing grain protein, and increasing yield. Jackson et al. (1964) showed that both P and K fertilization increased yield, test weight, and kernel size of spring-planted barley in western Oregon; these increases were more pronounced in years when yellow dwarf virus was present.

All of the previously cited effects might be considered direct effects because either N or P was being added as fertilizer and the N or P content of the crop was being increased. The major problem comes in evaluating and identifying a wide range of indirect effects, such as: (i) possible reductions in Se from S fertilization; (ii) increases in protein content of legumes from S, Mo, or P fertilization; and (iii) possible adverse effects of N and S fertilizers on micronutrient concentrations.

Probably the easiest beneficial effect to document is the increase in N content, and thus, indirectly, protein, of legumes when nutrients are added that increase N fixation by *Rhizobium*. Sulfur, P, Mo, and Ca are probably needed more luxuriantly by *Rhizobium* than by many of the host legume plants. These indirect beneficial effects are widely recognized. However, possible adverse effects are often more difficult to explain.

Possible toxicities and deficiencies of Se in the western states presents a complex problem. Selenium is not required for plants but is required for animals. Present experiments with plants have not established beneficial effects. However, in forage plants the range in Se concentrations that will cause toxicity or deficiency in ruminants is relatively small. Levels below 0.10 mg/kg of Se result in white muscle disease and frequent death of calves and lambs, and levels above 1.0 mg/kg start to cause Se toxicity (Allaway, 1971). Excess Se is accumulated in some plants growing on shale soils in parts of the Dakotas and Wyoming.

Sulfur fertilization can increase the yield of many legumes 5 to 10 times in many areas of the Pacific Northwest where Se levels are low (Westermann and Robbins, 1974). Thus an alfalfa hay yield of 1 t/ha with 0.10 mg/kg of Se could be increased to 6 t/ha and have the Se concentration diluted below 0.03 mg/kg without actually decreasing the total Se removed by the crop. A level of 0.03 mg/kg of Se and lower usually produces widespread white muscle disease.

Also, leaching a soil with sulfate salts will hasten the leaching losses of Se (Brown and Carter, 1969). With these effects, S fertilization, an essential practice for producing alfalfa hay and other legumes in the northwest states, frequently results in biologically significant reduced concentrations of Se in the forage produced.

In contrast to S fertilization, P fertilization frequently results in increased levels of Se in the forage (Carter et al., 1972). Rock phosphate frequently contains small amounts of Se, and P fertilization may increase Se uptake (Robbins and Carter, 1970).

21-11 RESEARCH DEVELOPMENT AND NEEDS

Today, farmers are making expert use of knowledge that took years to learn through research and development. Research effort in soil fertility must continue to provide answers to present and future crop production problems. The identification of specific nutrient deficiencies and establishing a basis for predicting response from fertilizer must remain in high priority for soil fertility-plant nutrition related research. At present, soil and plant analyses are the main tools for identifying deficiencies and predicting fertilizer responses, but refinements in those techniques are needed. Some fundamental studies on ion activities and concentrations are likely to improve soil test procedures. Minimum threshold levels of ion concentrations in soil solution need to be established for each crop throughout the growing season, and the nutrient release rates for soils need to be determined. Calibration of soil tests is a continuing process for assuring efficiency of the test employed as soils change under the impact of varied cropping and tillage practices, increased yield potential, and prior fertilizer treatments.

Soil fertility investigations in the future must be conducted by utilizing all crop cultural practices that can maximize crop yields. Many changing cultural practices are rendering some of today's knowledge on fertilizer use obsolete. Examples of needed research are given below.

21-11.1 Use of Fertilizer in Conservation Tillage

Conservation tillage is a management alternative currently gaining in popularity and slowly being adopted to reduce soil loss and conserve fuel on many agricultural soils in dryland farming regions throughout the West.

The reduced tillage and protective soil cover, however, are known to affect other soil processes, e.g., soil temperature, water infiltration rates, and the distribution of decayed plant material and applied fertilizer in the surface soil layer. Crop residues incorporated in the surface soil can immobilize N, can reduce nitrification rates, and might be phytotoxic to seedlings. Aeration is thought to change with a shift toward less oxidation and less mineralization of N with conservation tillage systems. Rooting density may also be altered, resulting in a soil plant system greatly altered from conventional tillage. The amount, placement, and timing of fertilizer application with these new systems must be determined.

21-11.2 Nitrogen Transformation and Movement in Soils and Improvement in Nitrogen Fertilizer Efficiency

Nitrogen fertilization is necessary for continued optimum crop production. Even though N is one of the most efficiently used plant nutrients, management can be vastly improved. Under fertilization results in low yields and restricts production. Overfertilization increases expenses without increasing returns, reduces yields, and poses a potential pollution hazard.

Most farmers in the semiarid region use less than optimum rates of N because of the uncertainties associated with rainfall and other factors. Field research must provide the information needed to predict optimum fertilization rates. Associated laboratory studies are also needed to better understand transformations and movements of N. These changes can cause unproductive losses of fertilizer N from soils. Research is a prerequisite to finding practices to minimize nutrient losses. In addition, research data concerning the use, transformation, and movement of N in soils provides assurance that only justified and rational measures will be instituted to protect the environment from excessive nitrates in water supplies.

21-11.3 Establishment of Secondary and Micronutrient Needs and Correction of Deficiencies

Previous research in soil fertility has emphasized N, P, and K. Less emphasis was placed on secondary nutrients and micronutrients. Yields of crops and forages have been increased by N, P, and K fertilization and superior cultivars. As a consequence a greater demand has been placed on soils to provide an adequate supply of other nutrients. Crop removal of available secondary nutrients and micronutrients, a decline in soil organic matter content, soil loss by erosion, and purer fertilizer materials have accentuated potential problems and increased the possibility that these elements may be limiting crop yields.

Intensified field research involving sources, rates, timing, and methods of application with different crops, management systems, and nutrients are vitally needed.

21-11.4 Effect of Fertilizer Use on Crop Diseases

Fertilizers can affect crop diseases. Even though the effect is generally beneficial, increased susceptibility of plants to diseases by fertilizer application has been reported. A luxuriant vegetative growth of wheat and other small grains resulting from fertilizer use can provide more favorable conditions for incubation of fungi and bacteria. However, optimum nutrition can also increase resistance of plants to diseases.

Huber et al. (1968) and Walker (1975) have shown that maintaining N in the ammonium form as long as possible will increase the percentage of NH_4-N taken up by a plant. Increased excretion of acidic ions accompanies uptake of N into the root rhizosphere; this increased uptake, plus increased acidification in the root rhizosphere, reduces the infection of take-all root rot. Younts and Musgrave (1958) showed that chloride can influence nutrient absorption and stalk rot in corn. Recent research by Powelson and Jackson (1978) has shown that the chloride ion can also influence the susceptibility of winter wheat to take-all root rot.

Keisling (1978) reported bacterial leaf spot in bermudagrass was reduced by increasing K rates. Potassium deficiency has also been reported to accentuate charcoal stalk rot in grain sorghum.

These examples indicate that the area of plant disease–plant nutrition relationships warrants expanded research.

21-11.5 Crop Quality

In a previous section, several effects of fertilizers on crop quality were discussed. The effects of increased N, P, and K seem to be well documented, but the effects of other essential nutrients on crop composition and nutritive value are not well understood. Measurement of quality factors are not well defined and require an integrated evaluation by scientists from a range of disciplines.

21-11.6 New Cultivars

As genetic yield capabilities are expanded, the continued need for fertilizer studies on new or improved cultivars is self-evident. Plant scientists are accumulating new information concerning the ability of genetic materials to better utilize specific nutrients. Iron-efficient lines of grain sorghum and soybean are now available. High protein hard red winter wheat lines are being utilized in developing improved cultivars. Aluminum-tolerant wheats, which endure very acid soils, have been identified. Possibilities for improved plant nutrition resulting from cooperative efforts between plant geneticists and plant nutritionists seem unlimited.

21-11.7 Energy Conservation

Fertilizer mining, processing, manufacturing, transportation, and application consumes considerable energy. As energy costs increase, fertilizer prices will probably increase. Some sources of fertilizers require less energy input than others. As new fertilizer materails are developed, they must be evaluated for efficiency and effectiveness both from a monetary and energy standpoint.

21-11.8 Impact of Fertilizer on Other Soil Processes

The long-term productivity of our soil resources depends on the maintenance of the soils in a desirable chemical, physical, and biological condition. Any deleterious effect can reduce crop production, whereas any improvement in soil processes can increase crop production and fertilizer efficiency.

Fertilizer salts, when used over a long period of time, can contribute to increased salinity. In addition, continued N use can result in potential soil acidity. Obviously, these factors need to be studied and predictive models developed.

The effects of continued, long-term fertilizer use on soil physical properties and biological characteristics of soils must be determined.

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