CHAPTER 3

Nitrogen use efficiency

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ABSTRACT

Nitrogen Fertilizer Use Efficiency (FUE) can be measured directly using ^{15}N labelling techniques or indirectly by the yield difference method. Both approaches have well defined limitations which must be understood. FUE rarely exceeds 50% based on yield and often is less than 20%. Mean recoveries of fertilizer N based on 37 well designed field experiments across the prairies were 38% in the whole plant, 32% in the soil and 30% lost.

About two-thirds of the total crop N uptake occurs in the first third of the growing period. The plant N is redistributed from anthesis onwards to reproductive plant parts. Incremental FUE decreases as fertilizer N rates increase. No fundamental differences in the ability of cereals to utilize soil or fertilizer N have been noted among varieties of wheat and barley. Suitable response curves for yield responses to N fertilizer have been developed for most crops grown in western Canada.

Water use efficiency (WUE) and FUE are dependent on each other. Drought stress, particularly near anthesis, may result in a dramatic decline in FUE and WUE. Management practices, including extended crop rotations, snow trapping and variable rate fertilization, which improve the use of either water or N, will in turn benefit the efficient use of the other.

Increases in protein concentration tend to lag behind grain yield increase. Drought stress will lead to higher protein content. Regional climate plays a larger role in determining grain protein concentration than does available N.

While N fertilizer rates based on soil tests provide good guidelines for yield and quality of most classes of wheat, such is not the case where malt barley is concerned; more data are needed to develop better guidelines for fertilizer management for barley, recognizing the price premium of malting over feed barley.

Nitrogen increases protein concentration and decreases oil content of canola, but these quality changes are small compared to the large positive effect of N fertilizers on yield. Additional information is required regarding the influence of N on other canola quality parameters.

Limited research has been conducted to describe the effect of N fertilizer on crop maturity, lodging and harvestability. Contrary to expectations, winter survival of winter wheat is not adversely affected when N is properly applied in the fall. Although N fertilizer has slightly increased a number of cereal diseases, few reports have shown significant yield reductions due to this interaction.

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Optimum fertilizer N management practices are a direct function of N source. In general, when properly applied and when soil test N, guidelines are followed, all N source are equivalent.

Greater N losses by denitrification and immobilization may result in lower FUE of fall- vs. spring-applied N fertilizer. Very little fall applied N is lost by leaching, particularly where ammonium and urea fertilizers are used. On the average, applying N in the fall has produced 94% of the yield increase of spring applied fertilizer, though this value is much lower in certain conditions. Application in the late fall when soil temperatures are low is advisable. Applying fertilizer to frozen soil or onto snow is not advised.

The key benefit of banding fertilizer N is reduced immobilization. Other benefits include reduced denitrification and enhanced positional availability to the plant. The comparative benefits and/or disadvantages of placement of N with the seed , sidebanding and dribble banding are discussed. More recent innovations, such as nesting of N fertilizer, show promise if application constraints can be overcome. Split application of N fertilizers have been found generally ineffective under the semiarid conditions on the prairies. A wide range of nitrification inhibitors have been tested which may improve FUE, but none have been introduced commercially in Canada to date.

CONTENTS

INTRODUCTION

Nitrogen nutrition of field crops in western Canada has been examined from an array of perspectives, including uptake dynamics, species requirements and response curves for grain yield and quality, climatic interactions, and optimum N fertilizer management. The underlying focus and goal of most research projects has been to improve optimum N fertilizer use efficiency (FUE). Fortunately, N fertilizer management practices that increase FUE in terms of crop yield fortuitously improve economic returns and minimize environmental contamination (Rennie, 1990). This chapter will therefore employ FUE as an index to examine crop N uptake and fertilizer management.

THE CONCEPT OF FERTILIZER USE EFFICIENCY

Measurement and Expression of Fertilizer N Use Efficiency

It is not the intent of this review to fully assess the techniques and merits of each method of FUE measurement. However, an understanding of the concept is required to allow proper understanding and interpretation of the relevant research data.

Two basic techniques are used in measuring FUE: "indirect" difference calculations and "direct" ^{15}N labelling. The indirect method is based on the difference in N content between fertilized and unfertilized plants:

$$\% \text{ FUE} = \frac{\text{(N uptake by fertilized plants - N uptake by unfertilized plants)}}{\text{N fertilizer added}} \times 100$$

The direct technique relies on ratios of the ^{15}N content of fertilized plants to the ^{15}N content of enriched N fertilizer.

$$\% \text{ FUE} = \frac{(^{15}\text{N content of fertilized plants x Total plant N content})}{^{15}\text{N content of applied fertilizer x Total N fertilizer applied}} \times 100$$

Indirect measurements do not account for the possible effect of added fertilizer on release and uptake of soil N (priming). Fertilizer N may stimulate microbial mineralization of organic soil N and simultaneously increase root growth and uptake of this N. Therefore, the indirect method may overestimate FUE. Direct measurements do not account for possible incorporation of ^{15}N fertilizer into the soil organic matter and subsequent mineralization of nonlabelled soil N, though careful experimental design can detect this dilution of ^{15}N. The pool of applied ^{15}N fertilizer could be diluted before plant uptake occurs and FUE would be underestimated. In most cases, estimates of FUE will be slightly higher if measured by indirect calculation compared to when measured by direct isotope ratios. However, a direct comparison of the two methods for field conditions in southern Alberta provided similar estimates of FUE (Roberts and Janzen, 1990). Recent work in Illinois suggested that the two techniques provided very different estimates of FUE and that caution must be used in interpretation of results depending on the method used (Torbert et al., 1992). However, closer examination of the data from the Illinois experiment show a good relationship between the two methods (Fig. 1). With careful measurement and replication of treatments and a complete understanding of the underlying principles of each technique, the resolution and accuracy of FUE measurements can be quite satisfactory. This conclusion is supported by previous work in Colorado (Porter et al., 1990).

Both techniques are valuable for use in studies that require a measurement of the relative effect of any factor on FUE. The direct method is appropriate for studies that require precise placement of fertilizers in field or greenhouse conditions. However, labelled fertilizers cannot be practically applied with field scale equipment, so final assessment of new fertilizer management techniques must depend on difference calculations. Field and growth chamber experiments in western Canada have illustrated the value of using the information gained with each method (Rennie and Rennie, 1973; Roberts and Janzen, 1990).

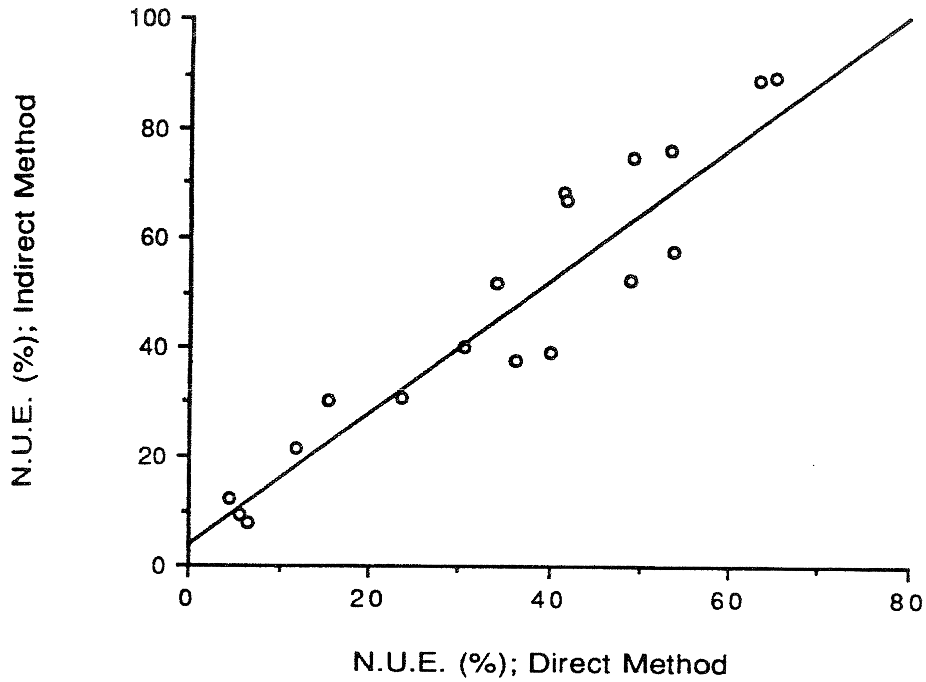

Figure 1. A comparison of direct (by ^{15}N ratios) and indirect (by difference) measurements of fertilizer N use efficiency (F.U.E.) for studies with corn at three sites in Illinois ($r^2 = 0.893$) (recalculated from Torbert et al., 1992).

A third method of measuring FUE is to calculate increases in plant N between increments of N fertilizer rates:

$$\% \text{ FUE} = \frac{\text{(Plant N content at F2 - Plant N content at F1)}}{\text{Increment of N fertilizer rate}} \times 100$$

where F1 and F2 are the low and high rates of N fertilizer. Although not often used in published research, this approach to FUE better recognizes the influence of incremental fertilizer rates.

Obviously, all of these calculations are functions of the complex reactions of the soil N cycle, and will be affected by changes in the soil and crop environment. Information about the growing conditions should be provided with any estimate of FUE. For example, FUE would be high for a crop planted on a N deficient soil and grown under ideal growing conditions. A crop grown on a N sufficient soil under poor conditions would require little fertilizer N and FUE would be low. The effect of the growth environment on N response and FUE will be examined more closely in the following sections.

The method of expressing FUE is also important to understanding the implications of any FUE study. FUE is most often expressed as a percentage of fertilizer nutrient used by the crop. An alternative is to measure efficiency in terms of crop yield per unit of fertilizer (e.g., kg grain per kg fertilizer N) or conversely, the amount of fertilizer N required to produce a unit of crop yield (e.g., kg fertilizer N per kg grain). Researchers have based FUE on N content of immature topgrowth, mature topgrowth, grain yield alone, and on the whole plant and soil system. The method of expression should reflect the goal of the experiment. If the intent of a project is primarily to increase grain yield and economic return from fertilizer investment, FUE for grain yield should be examined first. An experiment to study losses of N fertilizer should base FUE measurements on recovery in both the plant and soil. Therefore, in comparing results of research studies it is important to first examine the methods of FUE calculation and expression.

Fertilizer N Balances...Where Did the N Go?

A wide range of FUE values have been measured in various field experiments in western Canada. Generally, FUE based on grain yield rarely exceeds 50% and often is less than 20%. Substantially higher efficiency is not possible because applied N moves into soil and plant N pools other than the above-ground plant growth. A portion of the fertilizer N can be found in the root biomass, weed growth and soil organic matter including microbial biomass. The N unaccounted for is lost from the field through volatilization, denitrification, leaching and erosion. Due to these unavoidable transfers and losses of fertilizer N, it is impossible for FUE to approach 100%. Rather, the goal of fertilizer management is to increase the movement of N into the crop in preference to the various other pools of N, especially that lost from the system.

A number of field experiments have provided soil and plant data to indicate the fate of applied fertilizer N (Table 1). Even under ideal plot conditions, average total recovery of N fertilizer ranged from only 43% to 90%. The remaining N would have been lost to the atmosphere, leached below the rooting zone, removed by erosion, or taken up by weeds. Obviously, there remains substantial room for improvement of FUE by using the optimum rate, timing and placement of N fertilizers.

A large portion of applied fertilizer is used in microbial growth and is subsequently incorporated into the soil organic matter (Table 1). This N could be mineralized and taken up by crops in following years. Although the N is not immediately utilized in crop growth, it may play an important role in the long-term improvement of soil organic matter quality. Unfortunately, very little information is available to ascertain the long-term effect of residual fertilizer N. In an eight year study in North Dakota, approximately 50% of the applied N fertilizer was recovered by the crop in the first year, and and an additional 25% in the following years (Alessi and Power, 1973). Although the potential importance of this pool of N has been recognized in western Canadian research, sufficient data have not been collected to provide a measure of its effect on crop yields and long term fertilizer response (Campbell and Paul, 1978; Juma and Paul, 1979; Carter and Rennie, 1987; Mackay et al., 1989; Janzen et al., 1990). Further information on the significance of residual fertilizer N in soil organic matter rebuilding is given in Chapter 9.

FERTILIZER N RESPONSE OF ANNUAL CROP PLANTS

Nitrogen Uptake Dynamics

An elementary knowledge of the N uptake characteristics of a crop is invaluable in better understanding the time requirements for fertilizer application. Compared to plant dry matter production, N accumulates more rapidly in the early growing stages, then the rate of

Table 1. Average recovery of ^{15}N-labelled fertilizer after one growing season in crops and soil for several trials in western Canada.

Source	Crop	Recovery of N fertilizer Grain	Straw	Soil[1]	Total
		-------------------	(%)	-------------------	
Paul and Rennie, 1977	barley (10 sites)	17	11	31	59
Campbell and Paul, 1978	wheat (irrigated)	58	13	19	90
	wheat (dryland)	37	12	37	86
Juma and Paul, 1979	wheat	26	11	49	86
Tomar and Soper, 1981	barley	Whole plant = 40		46	86
Innovative Acres, 1983	wheat (9 sites)	32	18	18	68
Carter and Rennie, 1985	wheat (6 sites)	16	5	43	64
Swerhone et al, 1989	wheat (irrigated)	Whole plant = 32		16	48
	wheat (dryland)	Whole plant = 20		23	43
Bremer and van Kessel, 1990	wheat	Whole plant = 34		33	67
Janzen et al, 1990	wheat (3 sites)	Whole plant = 37		31	67
Mahli and Nyborg, 1991	barley (2 sites)	Whole plant = 37		38	75

[1]fertilizer recovered in soil organic matter

Table 2. Nitrogen fertilizer use efficiency (FUE) of various barley cultivars under three moisture conditions. FUE was calculated by the difference method of total plant N (from Grant et al., 1991).

Cultivar name	Cultivar class	Grain yield	Nitrogen yield	NUE
		(kg ha^{-1})	(kg ha^{-1})	(%)
Bonanza	standard malting	3175	105	48.3
Bedford	standard feed	3406	114	54.3
Virden	standard feed	3961	118	61.6
Heartland	short feed	3669	112	47.9
Duke	semidwarf feed	3353	113	55.2
Samson	semidwarf feed	3329	106	50.6

uptake diminishes as crop maturity approaches. Nearly two-thirds of the total N of spring wheat is taken up within the first one-third of the growing season (Fig. 2). This pattern of N requirement is similar for other types of cereals, and for canola (Clarke et al., 1990; Swerhone et al., 1990). In terms of growth stage, field studies in southwestern Saskatchewan showed N to accumulate in wheat plants faster than dry matter up to the shot blade stage (Campbell et al., 1977a). At this point, 70% of the N but only 50 to 65% of total dry matter had accumulated in dryland conditions. During these early growth stages, the plant N accumulation rate exceeded 4 kg ha^{-1} day^{-1} in conditions of nonlimiting available N. Nearly all of the plant N has accumulated at anthesis. Nitrogen is then redistributed from the plant leaves, stems and roots to the reproductive parts (Campbell and Davidson, 1979; Clarke et al., 1990). Accumulation of N in the developing kernels is usually similar to dry matter accumulation, although N transfer into the grain may be prolonged under ideal irrigated conditions (Campbell et al., 1990).

Nitrogen fertilizer is also rapidly recovered up to the shot blade stage (Fig. 3). Obviously, it is important for fertilizer N to be readily available during the early establishment of the crop. Conditions which do not allow rapid absorption of N in this stage will diminish FUE because later uptake mainly increases grain N concentration but does little to increase grain N content, which is mainly a function of grain dry matter (Clarke et al., 1990).

Crop Response to Fertilizer N, and Yield Predictions

Volumes of data have been collected to describe and predict crop response to fertilizer N in western Canada. This research has been used to prepare fertilizer recommendation guidelines by the various soil testing laboratories in each province. In many cases optimal economic efficiency has been obtained from N response curves. A complete treatise of this information is therefore not required. Rather, a brief overview of typical N response is appropriate.

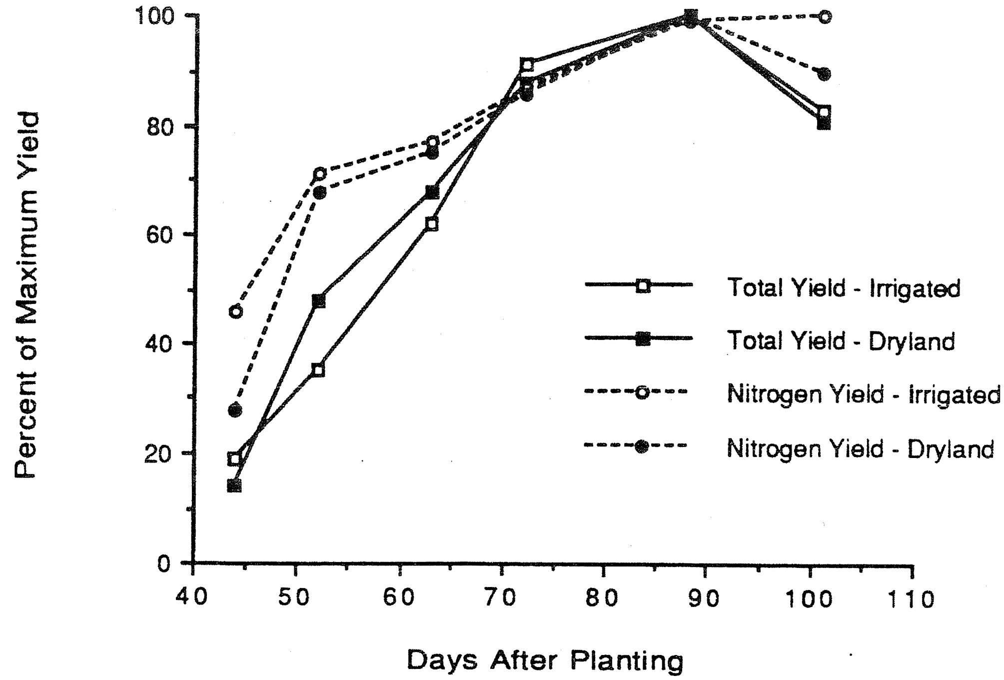

Figure 2. Accumulation of dry matter and N in irrigated and dryland spring wheat over a growing season (from van Kessel and Livingston, 1989).

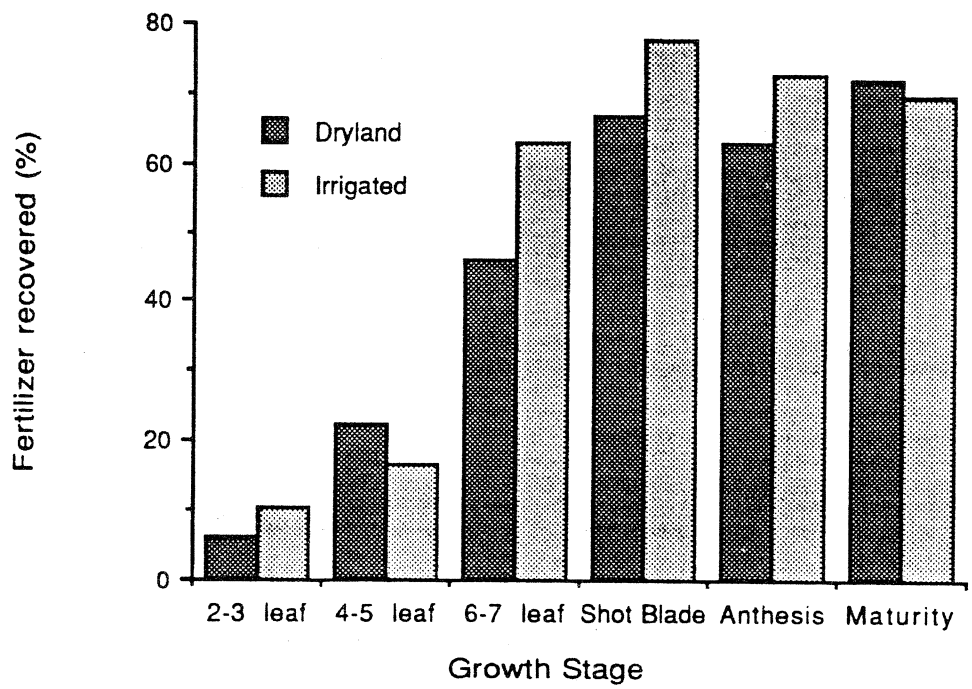

Figure 3. Recovery of deep banded ^{15}N-labelled fertilizer at various growth stages of barley (from Hartman and Nyborg, 1989).

Numerous empirical relationships of crop yield and N uptake have been derived for crops in the prairie provinces. Quadratic functions have most often been used in developing yield equations (e.g., Soper et al., 1971; Walker, 1975; Heapy et al., 1976a; Bole and Pittman, 1980b; Bole and Dubetz, 1986; Selles et al., 1988; Nuttall and Mahli, 1991). Extensive work with winter wheat in Saskatchewan has demonstrated that inverse polynomial equations accurately predict yields, and also provide a sound biological argument to the relationship (Fowler et al., 1989a,b; Fowler and Brydon, 1989a,b). In each case, the essential element is a decreasing yield response as fertilizer rates increase until a maximum yield is reached for each increment of added fertilizer N, the % FUE declines, eventually reaching zero at maximum yield. Predicted N requirements for maximum wheat yield range from 100 kg ha^{-1} to well over 200 kg ha^{-1} for various conditions (Soper et al., 1971; Walker, 1975; Selles et al., 1988; Fowler et al., 1989a; Gehl et al., 1990). The soil testing laboratories across the prairies have effectively developed yield equations and N fertilizer recommendations for various crops, based on this research. This has provided an invaluable management tool to farmers wishing to improve N FUE.

The relationship between incremental yield response, and FUE, has been widely reported (Campbell et al., 1977a; Read et al., 1982; Carefoot et al., 1989; Grant et al., 1991; Campbell et al., 1992b; Gauer et al., 1992). In a nine year study in southern Saskatchewan average FUE of spring wheat decreased from 27 kg grain kg^{-1} N fertilizer to 13 kg grain kg^{-1} N fertilizer as fertilizer rates increased from 25 to 100 kg N ha^{-1} (Campbell et al., 1992e). In a five year project in northeastern Saskatchewan, barley utilized 23% of applied N at a rate of 45 kg N ha^{-1} compared to 18% at 134 kg N ha^{-1}. In the same study, recovery of N fertilizer by canola dropped from 50% to 35% as the fertilizer rate increased from 45 to 134 kg N ha^{-1}. At the higher rate, increased N concentration in the grain partly offset the lower fertilizer N use efficiency based on yield (Nuttall, 1989).

FUE also falls as levels of available soil N increase. However, the ability of plants to utilize available soil N from increasing depths, relative to added N fertilizer, has not been well established and requires more research (Carefoot et al., 1989). Recent model development based on spring wheat fertilizer trials in southwest Saskatchewan does indicate that available soil N to 60 cm is equivalent to added N fertilizer for crop uptake in the first year of application (Selles et al., 1992).

Obviously, any factors which increase FUE will also increase the rate of yield increase per unit of N fertilizer. FUE can therefore be used for comparing fertilizer practices. In the same context, the factors which influence FUE should be documented with any equations that are developed to predict crop requirements for fertilizer N. Any future establishment of benchmark values for soil testing purposes must utilize best fertilizer management practices, with an underlying measure of FUE.

Cultivar Influence on N Requirements

New cultivars are continually being developed in western Canadian. It has been a concern that new varieties may have a different requirement for fertilizer N, due either to higher grain yield potentials or different FUE for added fertilizer. Projects have been implemented in recent years to assess the varietal influence on N requirements and fertilizer response.

Differences in yields between various wheat and barley varieties have been well documented. For example, the Canada Prairie Spring (CPS) and utility wheat varieties usually yield more than traditional hard red spring wheats. Similarly, feed type barley varieties often yield substantially more than malt quality barley varieties. Where varieties with very different growing characteristics have been compared, some differences in N requirements have been observed (Knott, 1974; Gehl et al., 1990). However, research has found little difference in the N requirements of various classes of wheat or barley bred for western Canada, let alone varieties of the same class (Wilkinson and Rennie, 1979; Briggs, 1991; Selles et al., 1991). A comprehensive study of various barley classes in Manitoba did measure differences in FUE (Table 2). These differences probably reflect differences in yield potential rather than any fundamental differences in ability to utilize N, as the higher yielding varieties generally had higher FUE. Overall, there was little difference in fertilizer requirements. Comparison of various spring wheat classes in Saskatchewan and in Manitoba lead to similar conclusions (Clarke et al., 1990; Gauer et al., 1992). While crop variety does affect FUE, there appears to be little indication that there should be different fertilizer recommendations for different varieties of wheat and barley grown on the prairies. Cultivars of other crop species have not been compared on the prairies. Of most interest would be potential differences between *B. napus* and *B. campestris* canola varieties.

INTERACTIONS OF WATER AND N USE EFFICIENCY

Water - An Essential Nutrient

In the arid prairie environment, water is generally the most limiting nutrient to crop growth under dryland conditions. Nutrient and water use efficiency are therefore inextricably dependent on each other. If either available water or nutrients is deficient, the efficient use of the other is impaired. This relationship has been the subject of numerous research projects in western Canada, and has been discussed in excellent reviews of wheat production research (Henry et al., 1986; Stepphun and Zentner, 1986). In particular, the interactive roles of water and N has been well documented.

Early work focussed specifically on water use efficiency by crops. A classic study in southern Saskatchewan with spring wheat established a minimum requirement of 12.5 to 15 cm of available water (spring soil moisture and growing season precipitation) to account for evaporative demand before any grain can be produced (Staple and Lehane, 1954). The Innovative Acres project confirmed this estimate with over 200 farm field measurements of spring wheat grown on a wide range of Saskatchewan soils (Fig. 4). From this data, the first centimeter of available water above the threshold value of 12.5 cm produces over 200

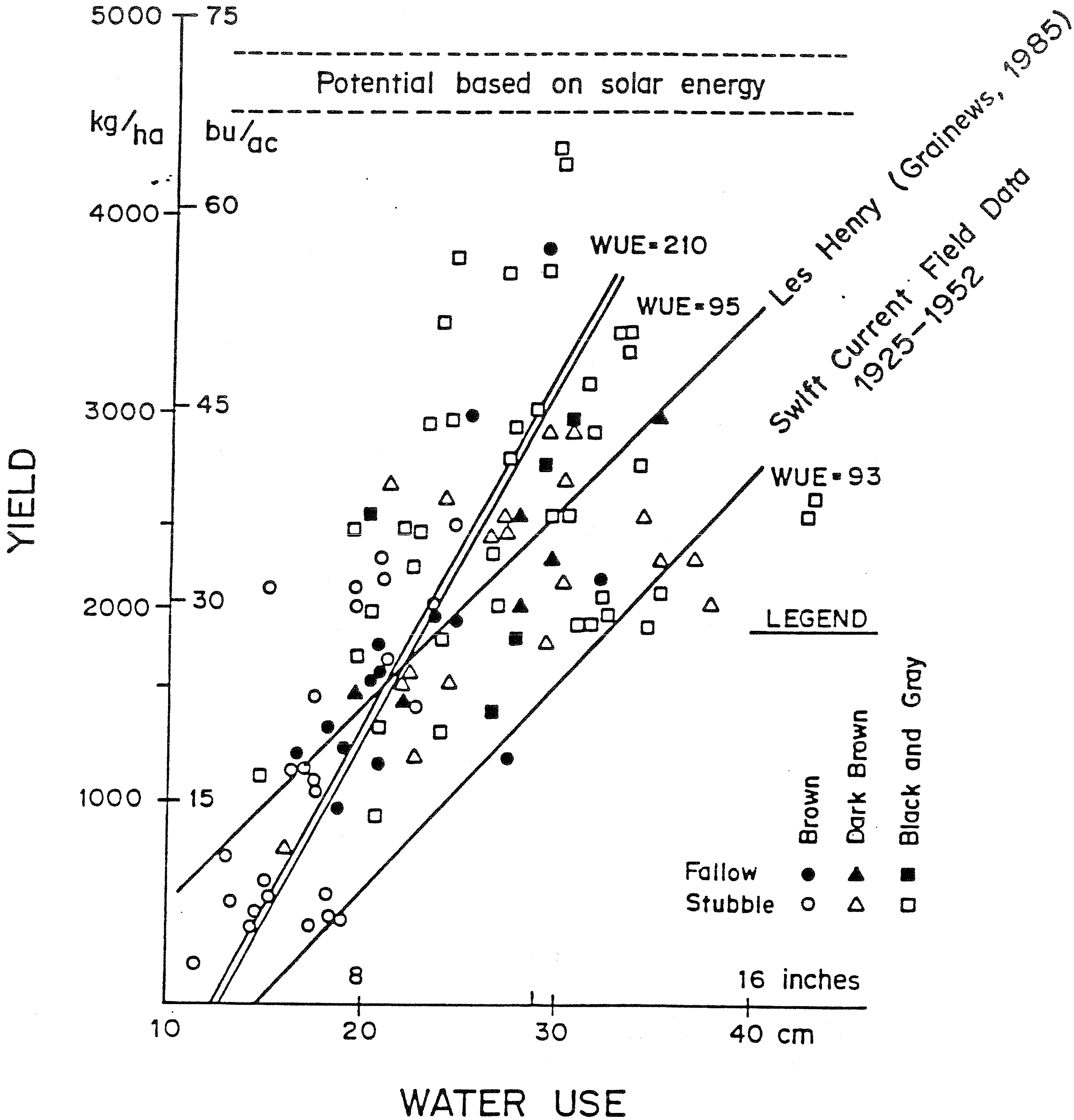

Figure 4. The relationship between yield and water use. The double line describes this relationship for the Innovative Acres Project. Each point is the field average of 10 measurement sites (Innovative Acres, 1986).

kg spring wheat ha^{-1}. The rate of yield increase then slowly declines until the maximum yield is reached. It is important to note that, compared to previous published data, the water use efficiencies measured in well managed fields of the Innovative Acres Project were substantially higher. The overall water use efficiencies measured were 80 to 90 kg ha^{-1} cm^{-1} for spring wheat, 100 to 120 kg ha^{-1} cm^{-1} for barley and 40 to 60 kg ha^{-1} cm^{-1} for oilseeds (Innovative Acres, 1986). Recent water use values from Swift Current for spring wheat also fall in a range around 100 kg ha^{-1} cm^{-1}, but emphasize the influence of N fertility (Campbell et al., 1988; Campbell et al., 1992d).

Nitrogen interacts positively with available water, and accordingly, increased N fertilizer use efficiency would directly result from practices leading to increased water use efficiency (Fig. 5). As continuous cropping and N deficiencies became more prevalent in western Canada, increased water use efficiencies were reported for fertilized crops (Warder et al., 1963; Ferguson, 1963; Hutcheon and Paul, 1966; de Jong and Rennie, 1969; Elliott et al., 1992). Nowhere is this more apparent than in the Grey soil zone, where N deficiency is more often a yield limiting factor than available moisture (Fig. 6). The focus of recent research has partly shifted from water use efficiency to N use efficiency as management guidelines for fertilizer application are improved.

Nitrogen Yield Response as Affected by Available Water

Crop yield and N use are reduced under extremes of wet and dry soil conditions. Under ideal soil moisture conditions the crop will rapidly grow and thereby FUE is increased. When dry conditions prevail, not only is crop use of fertilizer N reduced, but microbial growth is also slower, and N immobilization is prevented (Paul and Myers, 1971; Campbell and Paul, 1978). The N not used by the growing crop is then more subject to losses by ammonia volatilization, denitrification, and leaching and is less available to subsequent crops. In a three year study in Manitoba, wheat grown in high

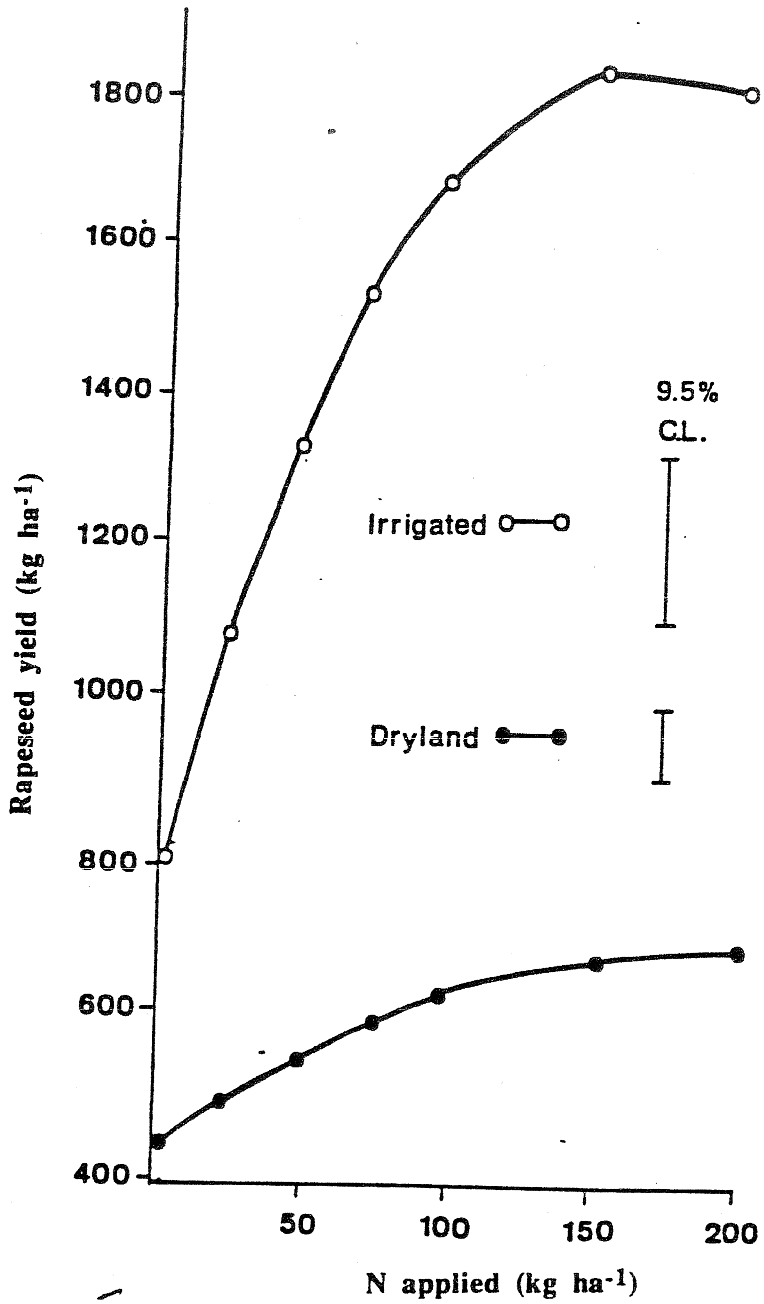

Figure 5. Effects of N on yield of rapeseed under irrigated and dryland conditions (mean data of eight site-years for each moisture regime) (Henry and McDonald, 1978).

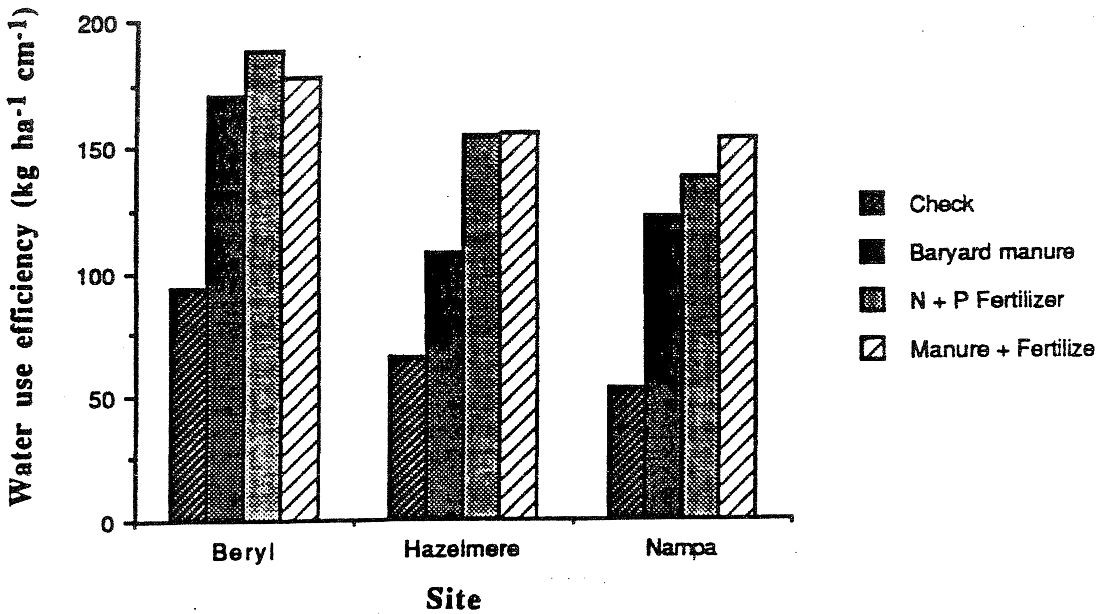

Figure 6. Average water use efficiency over five years of barley grown on Grey Wooded soils at three sites in northern Alberta. The manure treatment (134 tonnes ha^{-1}) was applied at the beginning of the five year trial, while the fertilizer treatments were applied annually (from Hoyt and Rice, 1977).

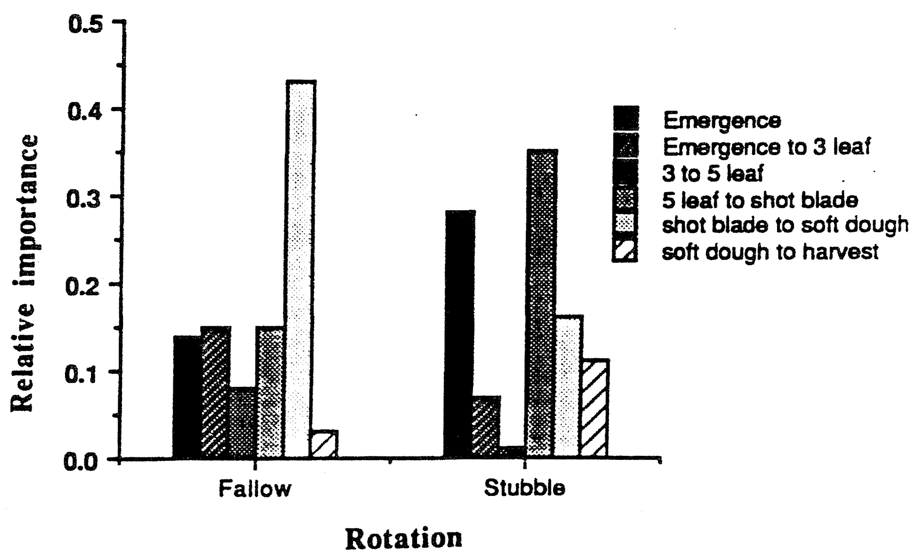

Figure 7. Relative importance of precipitation at various growth stages of spring wheat for stubble and fallow crops (from Campbell et al., 1988).

moisture conditions maintained a higher FUE over increasing rates of N fertilizer than wheat grown under moderate moisture conditions (Gauer et al., 1992).

Benchmark studies to establish N response curves for various crops have often found that available moisture must be included as a determining factor in yield equations for predictions to be significant. Nitrogen response curves which account for available moisture have been developed and published for wheat (Hinman, 1974; Campbell et al 1977a, 1977b; Fowler, 1986; Campbell et al., 1988; Gehl et al., 1990; Campbell et al., 1992b; Selles et al., 1992), for barley (Heapy et al., 1976a; Heapy et al., 1976b; Bole and Pittman, 1980a; Bole and Pittman, 1980b; Grant et al., 1991) and for canola (Krogman and Hobbs, 1975; Henry and MacDonald, 1978). A synergistic effect of N and water on yield has often been realized. The yield of spring wheat grown in lysimeters under field conditions in southwestern Saskatchewan was increased 46% by N fertilizer, 70% by additional water, and 235% by water plus N (Table 3). Similar results have been recorded in many of the other published studies.

Timing of Rainfall

The timing of rainfall is often as important as the amount of rainfall received. Crops grown under dryland conditions must rely on a combined supply of soil moisture available at seeding time and growing season precipitation. As the most critical periods in crop growth is just prior to and during anthesis, a shortfall in precipitation in this period will have a severe effect on grain yield. At this point, most of the spring soil moisture has been used and the crop is dependent on rainfall. Calculations of barley yields in southern Alberta suggested growing season precipitation affects grain yield three times more than spring soil moisture for fallow crops and twice as much for stubble crops (Bole and Pittman, 1980b). This is reflected in the equation:

$$\partial Y/\partial N = 0.256 - 0.0818\ N + 0.0257\ W_S + .0800\ GSP$$

Table 3. Yield of spring wheat with additions of N fertilizer and water (from Campbell et al., 1977b).

Moisture treatment	Nitrogen fertilizer applied 0	21	41	61	82	123	164
	(kg ha^{-1})						
	Grain yield (kg/ha)						
Dry	1617	1578	1754	1732	2028	2192	2367
Wet	2745	3798	4154	4395	4395	5425	4883

Table 4. Spring wheat yield increase or decrease as affected by precipitation and evaporation throughout the growing season (from Read and Cameron, 1981).

Time period	Yield Increase
	(kg ha^{-1} cm^{-1})
Spring soil moisture	29
May rain	55
June rain	35
July rain	35
June evaporation	-10
July evaporation	-51

Table 5. Average spring wheat moisture use and climatic moisture deficit (rainfall - evapotranspiration) for multiple site/years in Saskatchewan (from Nuttall et al., 1979).

Growth stage	Moisture use	Moisture deficit
	(cm)	(cm)
Planting to emergence	1.80	-0.77
Emergence to jointing	2.81	-0.69
Jointing to heading	7.30	-2.35
Heading to soft dough	7.77	-5.05
Soft dough to ripe	2.05	-4.71

which describes grain yield response to N fertilizer where Y, N, W_S and GSP were the grain yield (kg ha^{-1}), N fertilizer rate (kg ha^{-1}), spring soil water and growing season precipitation (mm), respectively. This indicates that the crop response to N fertilizer was over three times more dependent on growing season precipitation than on spring soil moisture. Similar conclusions can be drawn from studies of spring wheat (Staple and Lehane, 1954; Campbell et al., 1988).

Stress due to drought and high temperature near anthesis (usually in mid to late July in western Canada) will lead to a dramatic reduction in both water and N use efficiencies (Table 4). This is apparent for both stubble and fallow crops, although adequate available water is more often a restricting factor throughout the growing season for stubble crops (Fig. 7). Unfortunately, the growing period when moisture use is highest often corresponds to the climatic period when moisture deficit is highest, as indicated by a four year study at a number of Saskatchewan sites (Table 5).

If excellent spring moisture conditions are followed by drought, heavy additions of N may reduce yields. The added N leads to larger leaves and increased transpiration and soil moisture use. As a consequence, the fertilized plants then suffer more severely from drought and exhibit inefficient water and N use (Campbell et al., 1977a). In contrast, plants stressed early in the growing season may recover somewhat if well supplied with water at later stages (Campbell and Davidson, 1979a; Campbell and Davidson, 1979b; Campbell et al., 1981; Davidson and Campbell, 1984).

Fertilization of Variable Landscapes

Water and N use by crops growing at various slope positions have been the subject of several field studies in Saskatchewan. The spatial variability of soil nutrients and available water in rolling landscapes has been a constant barrier to efficient use of water and fertilizer nutrients. The initial focus of the influence of fertilizer on water use efficiency concluded fertilizer additions increased yields and water use efficiency at each slope position (Table 6). Further analysis of this data, as well as Innovative Acre field trials, revealed that, although fertilizer application to infertile knolls often led to large proportional yield increases, the largest actual yield and yield increase, and therefore the most efficient use of fertilizer usually occurred on the moist lower slopes. Based on this premise, preferential fertilization of knolls over lower slopes was not recommended (Kachanoski et al., 1985).

Recent and current projects have continued to examine fertilizer requirements based on slope position (Elliott et al., 1990; Cowell and de Jong, 1990; Pennock and Anderson, 1992). Separation of landscape areas is essential to avoid over- and under-fertilization of particular areas of a field (Tomasiewicz, 1990). Conceptual separation of fields into landscape units based on slope curvature (and consequently soil water and nutrient variability) appears to be a potential tool in soil sampling and fertilizer application (Pennock et al., 1987; Pennock and Anderson, 1992).

Accurate fertilizer application at rates required by each area of a field (as opposed to a blanket fertilizer application) would certainly improve crop yields with less economic and environmental cost. Recently, application equipment and technology has become available to farmers for changing application rates while applying fertilizer. The ongoing refinement of airseeders and similar equipment has provided one such option. Variable N and P deficiencies over a field require equipment which can apply each fertilizer as needed. While remote sensing and location tracking equipment may play an additional role in this regard in the future, accurate soil sample diagnostics, and recommendations for representative landscape units, coupled with more precise fertilizer applications, are a first priority to the producer.

Rotational Management for Water and N Use Efficiency

Management practices which conserve and make more efficient use of soil water and precipitation will lead to more efficient N use. Summerfallow rotations accelerate the

Table 6. Yield and water use efficiency of spring wheat as affected by fertilization of stubble and fallow fields in rolling landscapes (from de Jong and Rennie, 1969).

Slope position	Yield		Water use efficieny	
	Control	Fertilized	Control	Fertilized
	($kg\ ha^{-1}$)		($kg\ ha^{-1}cm^{-1}$)	
		Stubble		
Knoll	1200	1690	46	65
Upper	1320	1650	58	73
Lower	1270	1660	61	75
Depression	1660	1920	72	80
		Fallow		
Knoll	1380	1690	61	74
Upper	1560	1860	69	83
Lower	1470	1860	65	82
Depression	1890	2330	74	93

Table 7. Average grain yield and protein concentration of spring wheat in crop districts in Saskatchewan for the period 1980 to 1989 (from Saskatchewan Agriculture and Food, 1989).

Crop district	Locations in Saskatchewan	Grain yield	Protein content
		($kg\ ha^{-1}$)	(%)
1 (Estevan/Moosomin)	Southeast	1602	14.5
2 (Regina/Weyburn)	South-central	1582	14.3
3 (Swift Current/Assiniboia)	Southwest	1481	14.4
4 (Maple Creek)	Southwest	1444	14.0
5 (Yorkton/Wynyard)	East-central	1896	13.5
6 (Saskatoon/Watrous)	Central	1664	14.4
7 (Wilkie/Kindersley)	West-central	1834	14.0
8 (Melfort/Tisdale)	Northeast	1822	13.8
9 (North Battleford/Meadow Lake)	Northwest	1931	13.6

release of soil N at a time when no crop is growing. Leaching and gaseous losses of N during a fallow year are a hindrance to improvement of N use efficiency on the prairies. A move towards continuous cropping, especially with perennial forages in rotation, would be a major step towards agronomic and environmental sustainability in terms of N as a nutrient or a pollutant (Campbell et al., 1992e). For a complete discussion of this topic, the reader is referred to the review *Crop Rotation Studies on the Canadian Prairies* (Campbell et al., 1990), with particular note of the sections *Soil Moisture* (pp. 49-61) and *Nitrogen and Phosphorus Dynamics* (pp. 62-69).

Snow capture has proven important to reducing risk of stubble cropping (Campbell et al., 1986; Campbell et al., 1992a). Furthermore, moisture gained from practices such as stubble stripping may lead to better use of available N (Fig. 8). Continued adoption of similar practices both on farms and in conjunction with fertilizer management research will lead to improved FUE.

GRAIN QUALITY RESPONSE TO N FERTILIZATION

In addition to its effect on crop yield, fertilizer N accumulates in grain as an integral component of all proteins. Grain protein concentration is an important economic criterion which must be considered in any N fertilizer study as an additional indicator of N use efficiency. In addition, N indirectly affects grain quality characteristics, such as seed size and weight ('plumpness'), baking quality, and oil content. Important crop characteristics which affect production potential of a crop including days to maturity, disease resistance and lodging are also influenced by available N. Western Canada has developed a world-wide reputation for the high quality of its grain crops grown for export markets, and producers and scientists have striven to maintain this quality. Most N fertilizer research has dealt with wheat protein content, with a few projects using barley or canola as test crops. Information for other crops, if available, is not published. The end use and therefore the quality characteristics of the produce differ among crops. Therefore, this section will

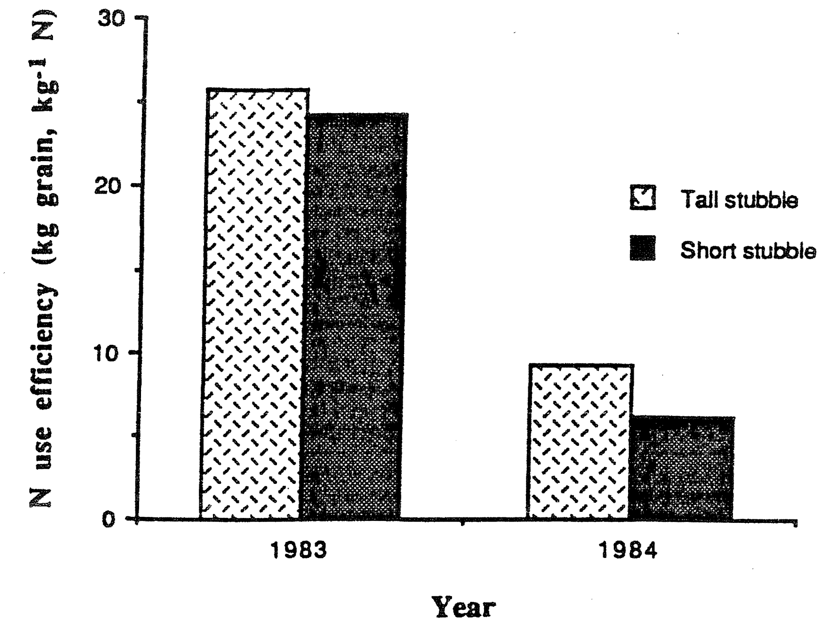

Figure 8. Nitrogen use efficiency (in terms of soil and applied N) for spring wheat grown in rotations with and without the use of tall stubble strips to capture snow (from Campbell et al., 1986).

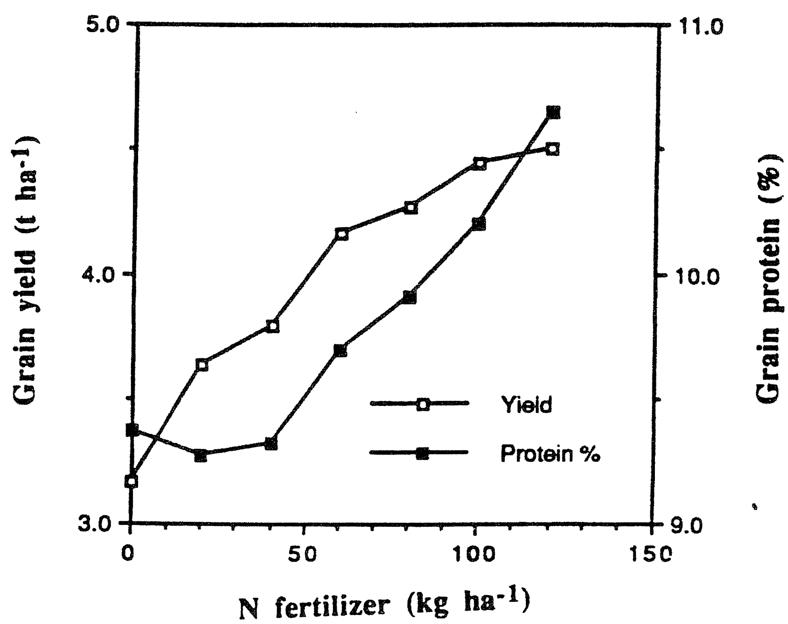

Figure 9. Grain yield and protein content of irrigated soft white wheat in response to N fertilizer (from Bole and Dubetz, 1986).

briefly review the relevant research which has studied the effect of N on the quality of wheat, barley and canola in the Canadian prairies.

Wheat

The quality parameters of the various wheat classes (hard red, soft white, Canadian prairie spring (CPS and durum) are diverse. For example, a premium is paid for High Protein (13.5% protein) and Very High Protein (14.5% protein) hard red wheat, an additional incentive for adding N fertilizer. A minimum of 11.5% protein level is suggested for milling-quality winter wheat; grain with a lower protein concentration is poorly colored and usually grades as feed wheat (Fowler and Brydon, 1988; Campbell et al., 1990b). In contrast, low protein is preferred for soft wheat destined to pastry flour production and medium protein is required for CPS wheat used for making flatbreads (Dexter et al., 1982). The characteristics required for utilization of each wheat class has been reviewed in *Wheat Production in Canada, A Review* (Fulcher, 1986; Matsuo, 1986; Preston, 1986). Recommendations for N fertilizer should reflect the quality goals of each wheat class. Nevertheless, the trends in protein response to N fertilization for the various wheat classes tend to be similar and can be discussed together.

The concurrent effect of N on wheat grain yield and protein concentration has been well documented (Alkier et al., 1972; Partridge and Shaykewich, 1972; Knott, 1974; Grant et al., 1985; Campbell et al., 1977b; Bole and Dubetz, 1986; Fowler and Brydon, 1988; Johnston and Fowler, 1991a; Gauer et al., 1992). Increases in grain protein concentration in response to additions of N tend to lag behind increases of grain yield (Fig. 9). When soil N is very deficient, both plant yield and total plant protein yield will rapidly increase with additions of N fertilizer. However, as with other nutrient constituents of plant tissue, protein concentration may be at first diluted by rapid plant growth in response to the first increments of fertilizer. Protein concentration begins to increase when available N exceeds the minimum crop requirements for additional grain yield. As the rate of increase in grain yield diminishes with increased rates of N, the protein concentration continues to increase. For this reason, a critical protein concentration has been suggested as an indication of N sufficiency (Fowler and Brydon, 1988; Fowler et al., 1989b). Protein concentration will continue to increase after the grain yield curve levels off. For higher yielding varieties, protein concentration is slower to respond to N fertilizer.

Naturally, any yield-limiting factors will contribute to higher protein concentrations. Drought and heat stress are the primary reasons for the relatively high protein concentration of wheat grown under dryland conditions in western Canada, particularly in the Brown soil zone. Early studies recognized the fact that local differences in climate and soil played a much larger role in determining grain protein concentration than did fertilizer application (Rennie, 1956; McKercher, 1964). For example, the moist climate and low organic matter content of Grey Luvisol soils result in higher yields but lower protein concentration of wheat crops in comparison to grassland soils. Wheat from crop districts in southern Saskatchewan has lower average yields but higher average protein concentrations than wheat from northerly crop districts (Table 7). Variation in protein is much smaller than for grain yield; while average grain yields differ by as much as 34%, average protein concentration only varies by 7%. Crop rotation has a similar effect on wheat protein; failure to apply sufficient N to stubble crops may lead to low yields of low protein grain (Campbell et al., 1983, 1992c).

Under field and controlled conditions, a higher rate of N is required to attain a given protein concentration under moist, and particularly irrigated, conditions (Sosulski et al., 1963; Hutcheon and Paul, 1966; Campbell et al., 1977b; Dubetz, 1977; Campbell et al., 1992c). Even so, total protein yield (and therefore N use efficiency) remains highest in moist conditions (Fig. 10).

High temperature, especially during grain filling, has a combined effect of aggravating moisture stress and increasing protein metabolism. Trials under controlled growth room conditions have demonstrated the very important role of temperature during

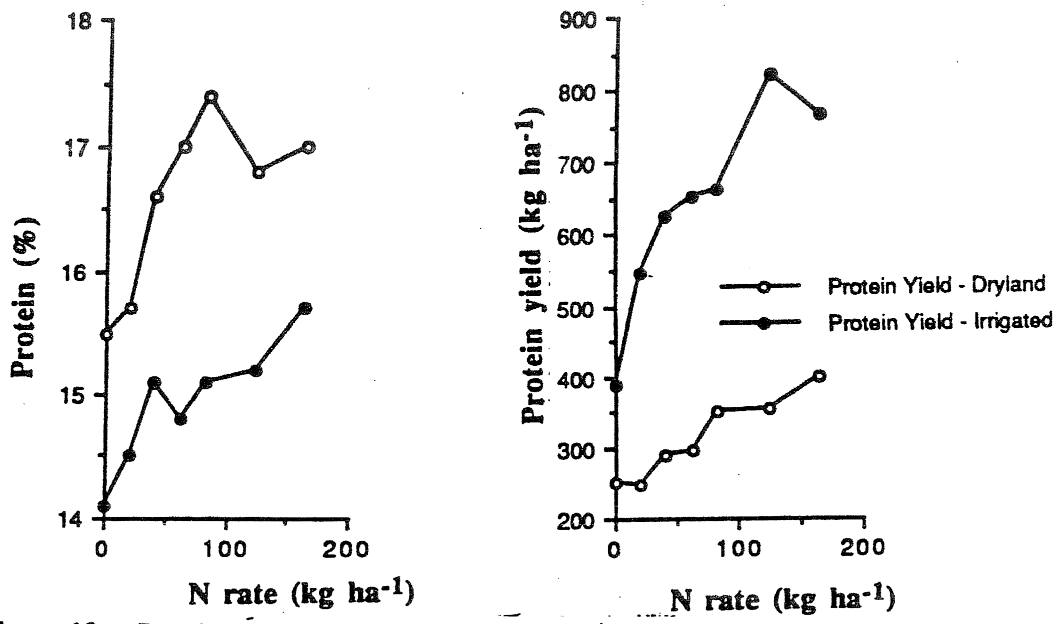

Figure 10. Protein concentration and protein yield of spring wheat under dryland and irrigated conditions (from Campbell et al., 1977b).

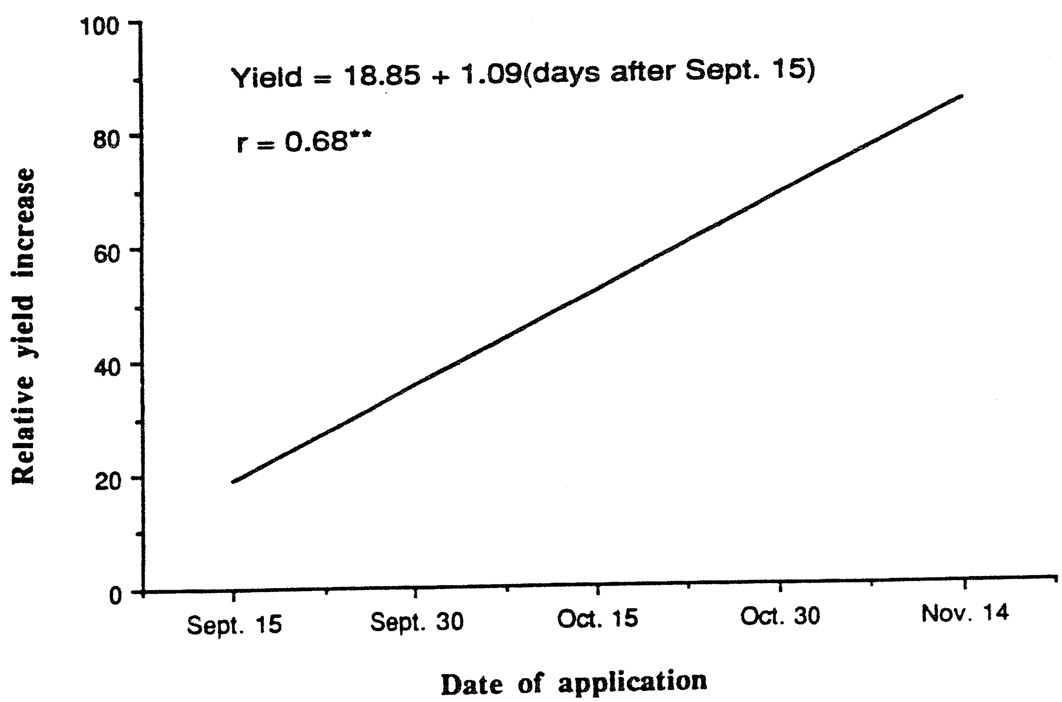

Figure 11. Yield increase of barley from application of urea fertilizer applied on various dates as a percent of yield increase due to spring fertilizer application (from Mahli and Nyborg, 1990).

seed set in determining grain protein (Sosulski et al., 1963; Campbell and Davidson, 1979b; Campbell et al., 1981).

In addition to grain protein concentration, other quality parameters may be affected by N addition. Kernel weight may be slightly decreased by N fertilization (Dexter et al., 1982; Campbell et al., 1992c). However, most experiments have concluded that N fertilizer has little effect on grain weight, especially in comparison to the effect of available moisture (Campbell et al., 1977b, 1983, 1990; Fowler et al., 1989a).

Barley

The two end-uses of barley, malt production and livestock feed, have opposing goals in grain protein concentration. While a high protein concentration is a positive quality for feed, maltsters prefer a low protein barley for their product (Table 8). Barley yield and protein both respond strongly to fertilizer N. There are no specific market premiums for high protein feed barley, so a management strategy which fertilizes to obtain maximum economic yield is logical. Substantial premiums have frequently been paid for malt quality barley, so there is some concern for the effect of N fertilization on malt quality. An early 6-year study concluded that N fertilizer had little effect on malt quality from a practical standpoint (Larter and Whitehouse, 1958). However, closer examination of the results of this study reveals that N fertilizer rates did not exceed 25 kg N ha^{-1}, and the treatments were confounded by additions of P fertilizer. Furthermore, these low rates of fertilizer did in fact increase grain protein concentration by as much as 2 percentage points, often to levels unacceptable for malting by today's standards.

Recent studies have confirmed that N addition can markedly increase barley grain protein concentration (Walker, 1975; McGuire et al., 1979; Bole and Pittman, 1980a; Innovative Acres, 1987b; Nuttall et al., 1989). Prediction of percent protein based only on soil and fertilizer N has proven very difficult, due to the additional effect of precipitation,

Table 8. Quality standards for malting barley (from Prairie Malt Ltd., Biggar, Sask.).

Quality characteristic	Barley type	
	2 - Row	6 - Row
Protein content	10 to 12.5 %	10.5 to 13.0 %
Germination	96%	96%
Plumpness	80% > 2.4 mm	75% > 2.4 mm
Moisture	< 14 %	< 14 %
Peeled and broken	< 3 %	< 3 %

Table 9. Effect of N fertilizer on mean yield, protein concentration and oil concentration of canola grown at three sites in Alberta (from Bhatty, 1964).

Nitrogen rate	Seed yield	Seed protein content	Seed oil content
(kg ha^{-1})	(kg ha^{-1})	(%)	(%)
0	926	33.8	45.4
45	1104	34.2	44.8
90	1272	35.7	44.1

Table 10. Movement of ^{15}N - labelled fertilizers in a Chernozemic Black soil profile after application of 100 kg N ha^{-1} on September 30 (from Aulakh and Rennie, 1984).

Soil depth	Fertilizer N			
	Oct. 20	Dec. 1	April 27	May 27
(cm)	(kg ha^{-1})			
	Potassium nitrate			
0-15	80.8	66.0	52.0	46.2
15-30	10.5	20.7	24.3	21.4
30-45	1.1	3.1	3.5	4.0
45-60	0.0	0.0	0.6	1.4
	Urea			
0-15	99.7	95.8	84.8	76.4
15-30	0.1	2.6	6.0	11.6
30-45	0.1	0.1	1.8	1.6
45-60	0.0	0.0	0.1	0.1

temperature and cultivar characteristics. In dry, hot conditions, high rates of N fertilizer are most likely to produce protein levels that exceed malt requirements.

Other malting qualities have been only briefly studied in terms of N fertilization. Field experiments in Montana measured increases in barley diastatic power (from diastase, the malt enzyme responsible for conversion of starch to sugar), but a decrease in malt extract (McGuire et al., 1979). The Innovative Acres project in Saskatchewan measured a significant decrease in kernel plumpness in response to N application at two sites (Innovative Acres, 1987b). Again, cultivar and climate appeared to be the overriding controls of seed quality. Sufficient data are not available to allow us to make definite statements on fertilizer management for malt barley. Development of better guidelines for N fertilization, recognizing the price premium for malt quality barley over feed barley, may be warranted.

Canola

Canola is utilized primarily for oil, although canola meal, a by-product of oil extraction, is fed to livestock. Nitrogen additions are known to increase protein and decrease oil concentration (Bhatty, 1964; Nuttall, 1973; Krogman and Hobbs, 1975; Henry and MacDonald, 1978; Sheppard and Bates, 1980; Nuttall et al., 1987, 1989). It is essential to recognize that the effect of N application on yield has consistently been much larger than on either oil or protein concentration (Table 9). Cultivar selection and weather again generally play a more important role in canola product quality than does N fertilizer.

No research reviewed has critically examined the effect of N addition on canola grain chlorophyll content, nor erucic acid and glucosinolate content of the grain, oil and meal, respectively. Each of these factors must be low for canola to receive a premium grade. Information regarding fertilizer effect on these quality characteristics, particularly chlorophyll content, is needed.

Other Crop Quality Characteristics

Besides seed quality, N fertilizer may affect a number of physical crop characteristics which directly or indirectly influence field production and/or quality of grain, including crop maturity, lodging, disease resistance and survival of winter crops. These effects are often noted in field experiments, but rarely quantitatively recorded. This is unfortunate, considering the importance of each of these qualities to the farmer.

While it is generally understood that N fertilizer rates up to those recommended by soil tests will not significantly influence maturation, there is little in the literature to support or deny this guideline. Work with barley indicated no delay in heading date (McGuire et al., 1979; Briggs, 1991). At nine sites with winter wheat and fall rye, heading date was delayed once by one to two days and maturity date was delayed three times by two to nine days when N was applied (Fowler et al., 1989a). No discussion was provided to explain the circumstances of these occurrences. Better information is required to allow fertilizer management decisions of late seeded crops which may be subject to frost damage.

Very high rates of fertilizer N may produce a lush vegetative growth which may lodge with maturity. Certain barley varieties were severely lodged when grown under irrigation with high rates of N fertilizer (Briggs, 1991). An assessment of lodging would be valuable to any cultivar x fertility research.

There has been interest in the effect of fall N application on the survival of winter cereals. Conclusive evidence from winter wheat research shows broadcast and banded N fertilizer do not reduce winter survival. However, seed-placed applications, particularly with urea, requires caution due to the possibility of seedling damage (Fowler and Brydon, 1988; Campbell et al., 1990b).

Increased susceptibility of plants to disease has been attributed to N fertilization. Lush growth and nitrate accumulation in the root environment and in plant tissue associated with large N fertilizer applications apparently encourages growth of pathogens. Published accounts have described at least slight increases of browning root rot (*Pythium* spp.), net blotch (*Drechslera teres*), common root rot (*Cochliobolus sativus*), kernel black point (*Alternaria alternata*) and various leaf diseases (Vanterpool, 1935; Piening, 1967; Pittman and Horricks, 1972; Briggs, 1991; Conner et al., 1992). Increased disease ratings were not often associated with decreased grain yields, and the importance of a balanced supply of N, P and other deficient nutrients were duly noted. No published reports of N fertility studies in relation to canola diseases were found. Canola crops in western Canada have been severely affected by several diseases such as sclerotinia and blackleg in recent years. Future studies of canola agronomy should consider this possible interaction.

IMPROVEMENT OF FUE THROUGH MANAGEMENT OF FERTILIZER

As described in the preceding discussion, an array of crop and environmental factors determine fertilizer N FUE. The N must be readily available at the correct time for crop uptake in order to minimize gaseous and leaching losses and microbial immobilization. Correct rates, determined by growing conditions and economics, must be applied for the specific crop. Careful management can maximize FUE through application of fertilizer rates based on soil testing and by optimal timing of application and placement of the fertilizer. The crop will make best use of fertilizer which is in an available form in the rooting volume when required by the crop. This section will examine the influence of management decisions on N FUE. For a complete discussion of fertilizer placement options, the reader is referred to Chapter 7. In addition, Harapiak et al. (1986) presented a comprehensive review of N sources and placement for wheat production. The importance of efficient fertilizer use cannot be over-emphasized; these management decisions have enormous implications toward farm profitability and environmental sustainability.

Timing of Fertilizer Application

Fertilizer N not taken up by crop roots is subject to microbial immobilization and losses by denitrification, volatilization and leaching. It is intuitive that N applied just before or at seeding will be subject to such loss mechanisms for a shorter period of time, and will thus be more efficiently used by the crop.

The amount of N lost depends on the fertilizer form, application technique, and field conditions. Fall application of N fertilizer has become a common practice for many farmers for several reasons. Farmers in western Canada are faced with a short growing season, often with limited time in spring for fertilizer application in addition to seeding operations on their large landbase. Seedbed drying by spring application of fertilizer may reduce stand establishment and crop yield. Frozen and wet soils also pose an obstacle to early spring applications. Lower fertilizer prices and a more readily available supply of fertilizers may influence a farmer to apply fertilizer in fall months. These are all substantial reasons for fall fertilization. However, the lower fertilizer use efficiency, opportunity cost, and loss of stubble for snow capture provide arguments against fall application. This section will review research pertaining to N use efficiency as a function of application timing.

Detailed studies have measured the potential loss of N fertilizer from the time of fall application dates to spring. A portion of the fertilizer is incorporated into the soil organic matter through immobilization by microorganisms. Although this N is not directly lost, it is certainly less available for plant uptake early in the growing season, and may result in lower grain yields and FUE. Various studies have estimated immobilization to account for 10 to 50% of applied N fertilizer, with values ranging from 25 to 30% in most studies (Mahli and Nyborg, 1983a, 1991; Aulakh and Rennie, 1984, 1986; Heaney et al., 1984; Nyborg et al., 1990). Immobilization is intensified if the fertilizer is broadcast then incorporated with large amounts of straw, particularly in the more humid areas (Nyborg and Mahli, 1984; Mahli et al., 1989).

Warm and moist falls and saturated surface soil conditions during spring thaw are ideal for rapid denitrification. Several studies indicate denitrification to be the main avenue for loss of fall applied fertilizer; measurements of denitrification over the winter period to seeding indicate 10% to over 50% of N fertilizer can be lost (Mahli and Nyborg, 1983a; Aulakh and Rennie, 1986; Nyborg et al., 1990). In contrast, very little N fertilizer applied in fall appears to be lost to leaching (Mahli and Nyborg, 1983a; Heaney et al., 1984). Downward movement of nitrate fertilizers may occur, but the more common urea fertilizers are much less susceptible (Table 10). Delayed application of N fertilizer in fall until just prior to soil freezing will minimize potential losses by denitrification and leaching (Selles et al., 1989) but the farmer runs the risk of being caught by an early freeze-up.

A review of research in which direct comparisons of fall versus spring applied N fertilizer were made in field plots in western Canada confirms that fall application is usually less efficient in terms of crop yield and NUE (Table 11). The FUE of fall applied fertilizer was less, and on average for all experiments, N fertilizer applied in fall produced 94% of the yield increase compared to fertilizer applied in spring. In some cases, these studies indicate fall fertilizer application may in fact be as or more effective than spring applications. It must be emphasized that almost all of these experiments had fall fertilizer applied in late October, and the fertilizer was either banded or immediately incorporated. Less ideal management would reduce the efficiency of fall applied fertilizer. Also, these experiments generally used standard fertilizer rates across all sites. If the fertilizer rate exceeded the requirements of the crop, the separation of spring and fall treatments would be less well defined.

Denitrification involves the reduction of nitrate to nitrogenous gases by certain bacteria during anaerobic respiration. Nitrification and denitrification are dependent on soil temperature and moisture; both processes increase rapidly at temperatures above 5°C and near field moisture capacity (Mahli and McGill, 1982; Mahli et al., 1990). Farmers can partially avoid these conditions by delaying fertilizer application till late October, when the soil is cold (Mahli and Nyborg, 1985; Janzen et al., 1991). In an assessment of the effect of application date of N fertilizer in north-central Alberta, recovery of fertilizer N increased from 30% when urea was applied on September 19 to 70% when applied on November 4.

Table 11. Comparisons of fall and spring applied N fertilizers applied to annual crops in field plots in Western Canada. For further details, see footnotes.

Crop	Fertilizer source and placement	Fertilizer rate	Soil zone	Relative value of fall application		Source
				Grain yield	Grain NUE	
(site-years)		(kg ha^{-1})				
barley (3)	urea, band	60	1, 2	98	96	Bole and Gould, 1986
cereals (70)	urea, band	?	1,2,3,4	108	96	Bole et al., 1984
wheat (9)	urea, band	50	1	101	95	Campbell et al., 1992b
wheat (3)	urea, band	50	1	95	94	Campbell et al., 1986
w. wheat (4)	urea, band	60 to 100	1,3	93	--	Campbell et al., 1991
w. wheat (4)	urea, band	50	1	107	116	Campbell et al., 1990b
w. wheat (4)	A.N., broadcast	30 to 60	3	89	86	Grant et al., 1985
wheat (2)	urea, band	60	3,4	111	--	Harapiak, 1979b
w.wheat (2)	A.N., broadcast	40	1	104	96	Janzen et al., 1991
wheat (1)	A.N., band	40	2	94	79	Jensen and Nyborg, 1986
barley (7)	A.A.. band	60	1,2	98	99	Kucey and Schaalje, 1986
barley (2)	A.A., band	60	1	96	97	Kucey, 1986
barley (4)	urea, band	50	3,4	--	44	Mahli et al., 1989
barley (19)	urea, broadcast	50	3,4	60	57	Mahli and Nyborg, 1990
barley (4)	urea, band	50	3,4	--	63	Mahli and Nyborg, 1991

(Table 11 continued, next page)

Table 11. Continued.

Crop	Fertilizer source and placement	Fertilizer rate	Soil zone	Relative value of fall application		Source
				Grain yield	Grain NUE	
(site-years)		(kg ha^{-1})				
barley (4)	urea, band	56	3,4	84	71	Mahli and Nyborg, 1992
barley (29)	urea, band	70	1,2,3,4	99	92	Mahli et al, 1984
canola (12)	A.N., broadcast	67	3	90	89	Nuttall and Mahli, 1991
wheat (3)	A.N., broadcast	67	3	82	83	
barley (3)	A.N., broadcast	67	3	90	87	
flax (3)	A.N., broadcast	67	3	102	104	
barley (5)	A.N., broadcast	45	3	98	96	Nuttall et al., 1989
canola (6)	A.N., broadcast	45	3	97	94	
barley (8)	urea, broadcast	56	3,4	86	86	Nyborg and Mahli, 1984
barley (44)	urea, broadcast	56	3,4	53	49	Nyborg and Mahli, 1986
barley (2)	urea, broadcast	50	3,4	--	33	Nyborg et al., 1990
barley (6)	urea, band	56	3,4	59	54	Nyborg and Malhi, 1992
barley (16)	urea, broadcast	?	2,3	--	73	Paul and Rennie, 1977
barley (8)	A.A., band	58	3	--	65	Racz, 1979
barley (3)	A.A., band	52	3	98	--	Ridley, 1977
barley (25)	urea, broadcast	52	3	91	70	
wheat (7)	urea, band	50	1	98	--	Zentner et al., 1988

Note - 'Relative value of Fall Application' is compared to similar spring application of fertilizer, set at 100
- soil zones are designated as Brown (1), Dark brown (2), Black (3) and Grey (4)
- Fertilizer sources are ammonium nitrate (A.N.) and anhydrous ammonia (A.A.)
- all broadcast fertilizer applications were incorporated, with the exception of winter wheat trials
- most comparisons were selected for late October fertilizer applications

As a result, grain yield was similarly increased (Fig. 11). Nitrogen losses decline as the application date approaches the first freezing date of the soil. However, fertilizer application to frozen or snow covered soil is inadvisable (Grant et al., 1985; Selles et al., 1989; Campbell et al., 1991).

Fall fertilization appears to be a relatively safe practice in the arid Brown and Dark Brown soil zones (Table 11). Higher soil moisture and crop residue levels in the Black and Grey soils often increase denitrification rates. Also, the higher yields and N requirements of crops grown in the moister soil zones probably magnify the differences between fall and spring fertilization. An extensive field study in Alberta demonstrated this difference in soil zones for fall and spring broadcast and incorporated fertilizers. For the Brown, Dark Brown, Black and Grey soil zones, the relative yield response of fall compared to spring applied N was 97%, 86%, 73%, and 63%, respectively (Bole et al., 1984).

The source of N fertilizer is another factor to be considered in evaluating time of application (Table 10). Direct comparisons of different N sources consistently show nitrate fertilizers to be inferior to ammonium and urea fertilizers for fall application (Paul and Rennie, 1977; Mahli and Nyborg, 1983a; Nyborg and Mahli, 1986; Campbell et al., 1991). Under certain conditions, recovery of nitrate fertilizer is low even with spring application (Fig. 12). Few published results of the use of anhydrous ammonia as a fertilizer source were found, despite its widespread use on farms. A direct comparison of anhydrous ammonia, urea, and ammonium nitrate suggested anhydrous ammonia could be the most effective N source. However, the anhydrous ammonia was banded to 15 cm, while the other fertilizers were broadcast and incorporated to only 2 cm (Kucey and Schaalje, 1986). Additional study of fall and spring application of anhydrous ammonia may be warranted.

Timing of fertilizer application has an obvious effect on N FUE. The relative efficiency of fall and spring fertilization has been well documented. As a next step, recommendation guidelines for fall applications need to be developed which recognize N

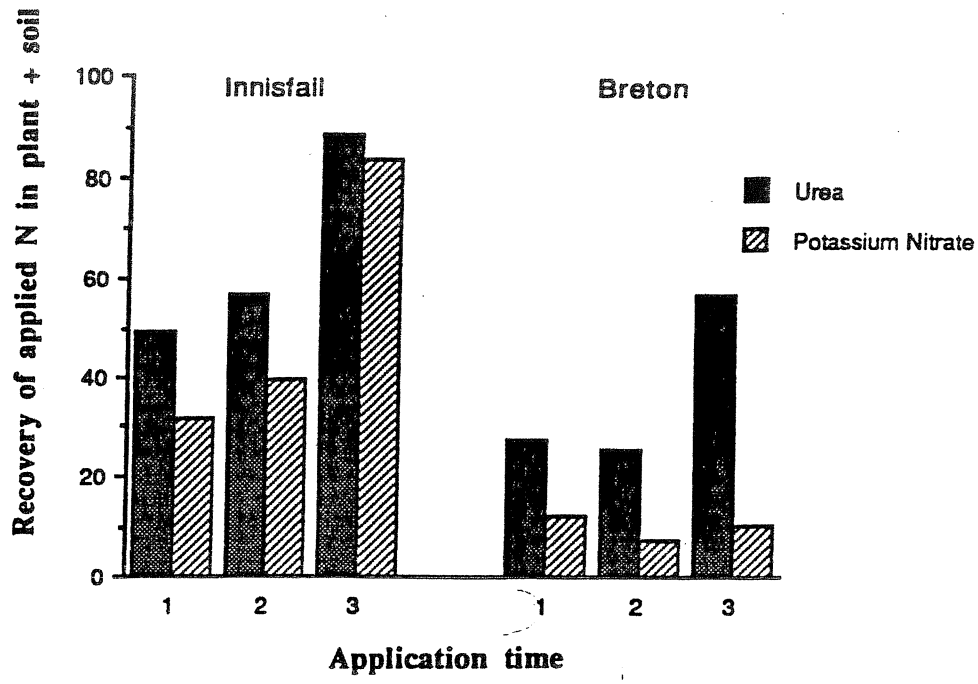

Figure 12. Percent recovery of ^{15}N labelled urea and K nitrate in plants and soil at harvest, for fertilizers applied in early October (1), late October (2), and at seeding (3) at two sites in Alberta (from Nyborg et al., 1990).

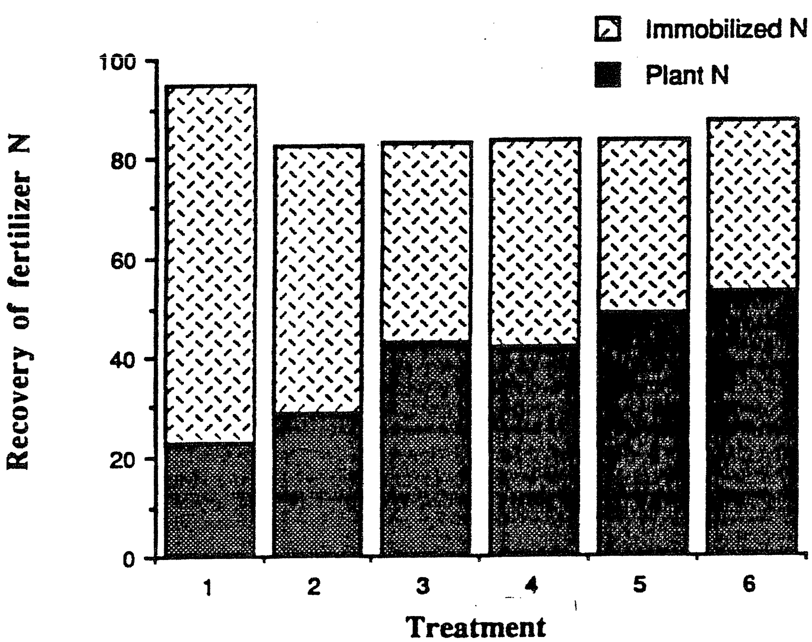

Figure 13. Recovery of fertilizer N in plants and in soil at harvest. Treatments are; 1 (fertilizer broadcast, straw incorporated; 2 (fertilizer broadcast, straw on surface); 3 (fertilizer broadcast, straw removed); 4 (fertilizer band, straw incorporated; 5 (fertilizer band, straw on surface); 6 (fertilizer band, straw removed) (from Tomar and Soper, 1981).

use efficiency (with specific reference to soil temperature and moisture), seasonal fertilizer costs, opportunity costs, and the effects of seedbed drying (spring application) and stubble disturbance reducing snow conservation (fall application). A regional focus on the Black and Grey soil zones, where yields and N fertilizer use are highest, is recommended. Proper timing of N application affords a simple and effective means of increasing FUE with little added effort or no extra expense to the farmer.

Nitrogen Fertilizer Placement

Ideally, fertilizer N is available to the entire crop root system for uptake. In this sense, fertilizer that is broadcast and incorporated would be the most efficient means of application, assuming the N remains available to the crop. Immobilization and loss of N from the rooting zone reduces the efficient use of broadcast and incorporated N fertilizer. Alternative placement techniques such as banding, nesting and seedrow placement have been developed to improve FUE. Band and similar placements concentrate N fertilizer, creating a localized and temporary soil environment which is unfavorable to microbial nitrification, denitrification and immobilization. In addition, proper placement of the band will make the N positionally more available to roots growing in moisture well below the soil surface.

The key benefit of band placement of N fertilizer is reduced immobilization (Tomar and Soper, 1981, 1987; Hartman And Nyborg, 1989; Mahli and Nyborg, 1991). Maximum immobilization occurs when crop residue and fertilizer are incorporated into the soil (Fig. 13). Actual loss by denitrification and leaching appears to be less affected by fertilizer placement. Reduced tillage coupled with fertilizer band placement should increase FUE for the current crop year.

Data summarized from field studies in western Canada confirm the consistent benefit of band placement of N fertilizers for spring seeded annual crops (Table 12). Grain yield and FUE both benefit from band placement. In contrast, broadcast N fertilizer has

Table 12. A summary of comparisons of banded and broadcast/incorporated fertilizer applications for spring seeded annual crops in Western Canada. All fertilizers were applied in spring prior to seeding.

Crop (site-years)	Fertilizer source	Fertilizer rate (kg ha^{-1})	Relative value of band vs. broadcast N*		Source
			Grain yield	Grain NUE	
wheat (9)	urea	50	106	--	Campbell et al., 1992b
wheat (3)	urea	50	107	--	Campbell et al., 1986
wheat (2)	urea	50	97	131	Carter and Rennie, 1984
wheat (2)	urea	40	100	128	Cho and Ahmad, 1969
	amm. nitrate	40	116	115	
wheat (?)	urea	50	118	--	Harapiak, 1979a
wheat (7)	urea	?	122	--	Harapiak, 1979b
barley (1)	urea	50	126	157	Hartman and Nyborg, 1989
wheat (1)	amm. nitrate	40	119	145	Jensen and Nyborg, 1986
barley (2)	urea	60	127	103	Kucey, 1986
barley (4)	urea	50	--	171	Mahli et al., 1989
barley (4)	urea	56	106	112	Malhi and Nyborg, 1992
	amm. nitrate	56	107	118	
barley (4)	urea	50	--	146	Mahli and Nyborg, 1991
barley (20)	urea	56	117	154	Mahli and Nyborg, 1985
barley (12)	urea	?	103	120	Ridley, 1977
barley (20)	UAN solution	56	125	--	Timmermans and Harapiak, 1981
barley (7)	anhydrous amm.	85	108	--	
barley (1)	urea	100	184		Tomar and Soper, 1981
wheat (7)	urea	50	120	--	Zentner et al., 1988

* See footnote for Table 11

proven as effective as fertilizer bands for winter wheat (Brydon and Fowler, 1988, 1989a; Campbell et al., 1990b, 1991). This effect is partly due to the loss of stubble protection and increased winter kill associated with contemporary banding equipment, which offsets losses of broadcast N. Fall seeded crops can also take up N in fall and early spring, thus preventing it from being lost.

Band placement is especially more effective for dry growing conditions, where it is often more positionally available to the root system. In dryland conditions, crop roots proliferate in moist soil at depth. Nitrogen incorporated to a shallow depth into dry soil will be inaccessible to the roots. If dry conditions persist, this N will not be leached into the rooting zone, and will instead be subject to immobilization and gaseous loss (Carter and Rennie, 1984; Hartman and Nyborg, 1989).

The effect of depth of banding and incorporation with field equipment has shown that a shallow band depth has advantages in reduced application cost and less seedbed disturbance. Recommendations have been for a 10 to 15 cm placement. Recent data from Swift Current showed no difference between a 5 and 10 cm band depth (Campbell et al., 1990b). A current study with anhydrous ammonia application at 44 sites in Saskatchewan has found no advantage to a 12.5 cm band depth over a 5 cm depth for knife openers, and only a small advantage for shovel openers (Fig. 14).

The acceptance and success of fertilizer banding in the past two decades can be largely attributed to the development of practical field scale equipment. Anhydrous ammonia applicator and distribution equipment are commonplace on the prairies. The rapid advance in airseeder design has provided a means of banding dry fertilizers. Better applicators have opened the door to reduced tillage, lower energy costs, better crop residue management, and more efficient use of available water and N. In a further attempt to improve FUE through placement technique, new innovative application technology is being developed and tested in western Canada. These are thoroughly discussed in Chapter 7. Below is an overview of these more recent developments.

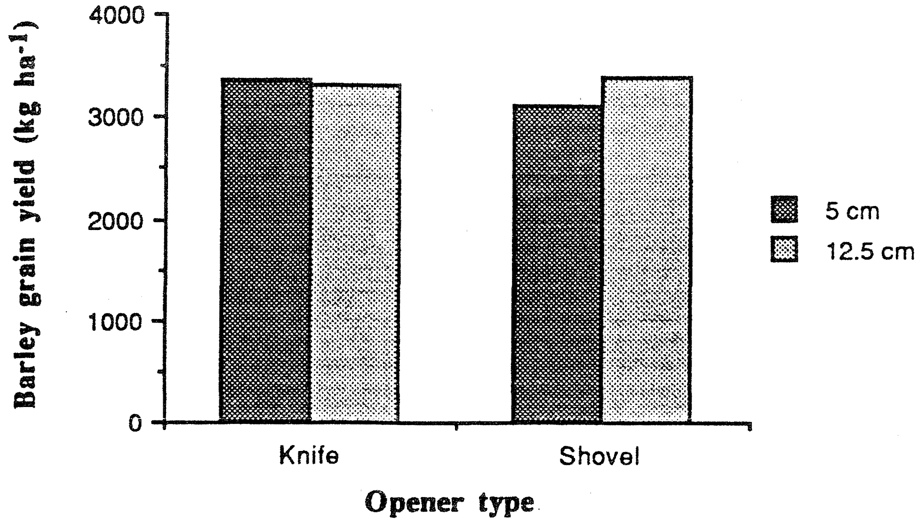

Figure 14. Yield of barley when fertilized with anhydrous ammonia using knife and shovel openers at two depths (from Campbell and Hnatowich, 1992).

Seedrow Placement: Seedrow placement itself is certainly not a new idea in fertilizer management. Low rates of N and P have been commonly applied with the seed since the introduction of fertilizer. However, high rates of fertilizer cannot be placed directly with the seed. The osmotic and certain toxic effects associated with concentrated fertilizers may reduce seedling survival and crop yield. For example, high levels of free ammonia near concentrated bands of urea are toxic to germinating seeds and seedlings. Seedling damage is maximum for urea fertilizers placed in a narrow band in dry, coarse textured soils with low organic matter contents. Small-seeded and winter crops are most sensitive (Dubetz et al., 1959; Nyborg, 1960; Molberg, 1961; Nyborg and Hennig, 1969; Ukrainetz, 1974; Toews and Soper, 1978; Campbell et al., 1991; Fowler and Brydon, 1991). The risk of crop damage as demonstrated by these research projects has resulted in continued recommendations for the use of very low rates of N fertilizer in the seedrow, despite the potential for maximum N efficiency with this placement. However, these same studies only considered seedrow placement with double disc drills, or in narrow seedrow bands in pot experiments. Recent seedrow placement trials with discers and airseeders in

Nyborg and Mahli, 1979; Heaney et al., 1987; Mahli et al., 1989, 1992). Compared to banding, the advantage of nesting is greatest for fall applied N fertilizer. Spring applied nests may impede uptake of N fertilizer to the crop, so are no better in effectiveness than bands in terms of FUE (Mahli and Nyborg, 1985). For this reason, initial work with field scale nest applicators have used winter wheat as a test crop. Experiments have established the best nest spacing and time of application (Janzen et al., 1990, 1991). Point injection of UAN solution has proven more effective than broadcast treatments of UAN solution or granular urea and ammonium nitrate (Table 13). Comparisons to band placement were not included.

Table 13. Relative yield and fertilizer N use of winter wheat fertilized by broadcast (BC) or nest applications of 60 kg N ha^{-1}. Comparisons are to point injected placement, set at 100 (from Janzen et al, 1990).

Fertilizer form and placement	Relative yield Grain	Relative yield Straw	Relative fertilizer N use Grain	Relative fertilizer N use Straw
UAN* solution (Nest)	100	100	100	100
UAN solution (BC)	83	81	64	61
Urea (BC)	78	77	56	59
Ammonium nitrate (BC)	84	80	74	68
Control	68	84	--	--

* Urea-ammonium nitrate

Equipment has been designed for fertilizer nest placement using high pressure pulses or spoke wheel applicators of liquid fertilizer. These implements provide a band-type placement with probably less draft requirement and seed-bed disturbance than conventional knife openers for banding, though these potential benefits have not been described in published literature. Immediate value for fertilizer nests has been recognized for winter crops and perennial forages. As the required equipment is refined, nest application may become a valuable fertilizer placement technique for all crops.

Split Applications: Foliar and broadcast N fertilization of growing crops has been investigated in various studies, usually with the goal of increasing grain protein concentration. Split applications of N fertilizer are commonly used in energy intensive agriculture in humid regions, such as in parts of Europe. This type of fertilizer application has not proven advantageous under the conditions of western Canadian agriculture. Greenhouse studies have indicated very little fertilizer N can be taken up from foliar applications (Alkier et al., 1972). A number of field trials have shown that late additions of fertilizer as foliar or broadcast application is an inefficient means of improving either grain yield or protein concentration (Innovative Acres, 1987a; Swerhone et al., 1990; Lafond, 1992).

Use of Nitrification Inhibitors

Chemical inhibition of microbial nitrification has been of recurring interest in various research programs. Nitrification inhibition involves the delay of one or more of the steps in the conversion of ammonium to nitrate to nitrous gases through a temporary toxic effect on the responsible bacteria. Delayed nitrification of urea and ammonium fertilizers, particularly when applied in fall, would reduce N losses by denitrification and leaching of nitrates, to the benefit of both the farmer and the environment. A wide range of chemicals has been proposed and tested for this purpose in prairie agriculture, but none have been introduced at the farm level. Because nitrification inhibitors have received attention world-wide only, a brief overview of their evaluation is presented.

Nitrapyrin (N-Serve™, 2-chloro-6-(trichloromethyl)-pyridine) has been recognized as a nitrification inhibitor for 30 years (Goring, 1962). Nitrapyrin has proven effective in growth chamber experiments, preventing the conversion of ammonium to nitrate (Nielsen et al., 1967; Campbell and Leyshon, 1980; Leyshon et al., 1980; Mahli and Nyborg, 1983b, 1988b; Aulakh et al., 1984; Mahli et al., 1988). In limited field work on the prairies, nitrapyrin appears to slow nitrification of fertilizers, but not ammonification of organic N nor immobilization of available N (Bailey, 1981; Mahli and Nyborg, 1983b, 1988b; Aulakh and Rennie, 1984).

Field and laboratory studies with ATC (4-amino-1,2,4-triazole hydrochloride) indicate this product to be very effective in preventing both ammonification and nitrification (Hogg and Halstead, 1977; Juma and Paul, 1979, 1983; Mahli and Nyborg, 1983b). Work in Alberta showed ATC to prevent overwinter losses of N fertilizer, making fall fertilization nearly as effective as spring fertilization (Mahli and Nyborg, 1988a,b). ATC appears to have significant potential as a nitrification inhibitor added to fertilizers, depending on cost-effectiveness.

Several other chemical nitrification inhibitors have been tested in the prairies. Thiourea, a metabolic inhibitor of the urease enzyme, has been used with some success in delaying hydrolysis of urea fertilizer and also inhibits nitrification (Mahli and Nyborg, 1979b, 1988a, 1988b). Carbon disulphide and its derivatives and xanthates were tested widely in Alberta (Ashworth et al., 1984). The xanthates inhibit urease as well as nitrification. Thiosulphate and sulphur anions have been tested, but these appear to inhibit the second step of nitrification, the oxidation of nitrite to nitrate. As a result, toxic levels of nitrite may accumulate (Gould and McCready, 1982; Janzen and Bettany, 1986). The urease inhibitor phenylphosphorodiamidate (PPD) and the nitrification inhibitor, dicyandiamide (DCD) both showed toxic effect to wheat and canola when added with N fertilizers (DeBeer and Yeomans, 1990; DeBeer Dagg and Yeomans, 1991). Dicyandiamide has the potential valuable property of being soluble in anhydrous ammonia (Ashworth and Rogers, 1981).

These chemical nitrification inhibitors have been proven effective in reducing N loss, and might increase FUE. Further development of these products for farm scale use must recognize their potential toxic effect (on the soil and surrounding environment), cost and availability to the farmer. Information on their effectiveness can be at least partly drawn from the substantial body of published work available. Addition of this technology to the developing fertilizer placement technology could lead to further increases in FUE.

RESEARCH PRIORITIES

Where should N fertilizer research on the prairies be concentrated in the next few years? First and foremost, FUE is influenced by a wide range of agronomic practices which impact the uptake of fertilizer N (and soil N). Further quantification in well designed field experiments of the relationship between N FUE and WUE could lead to major benefits to the grain industry.

A better understanding of soil N balances is required. For example, the residual effect of N fertilizer additions should be better assessed; N FUE may be higher than measured in single year experiments. These measurements will improve our understanding of fertilizer for crop use and their effect on the environment.

There are many deficiencies in the understanding of optimum N fertilization for canola. Are there real differences in the N requirements of *B. napus* and *B. campestris*? How does the N nutrition of canola relate to various canola diseases? To what extent is canola seed meal and oil quality affected by N fertilization?

Crop quality parameters should be assessed in all fertilizer N research projects. This does not mean that the relationship between N fertilization and protein concentration has not been well researched. Greater understanding, however, of the relationship between N and the malting quality of barley could lead to major benefits to the farmer growing this crop. Similarly it is regrettable that other quality factors such as maturity and lodging have been poorly described if at all in N field fertilizer experiments; but these are of great importance to farmers.

Nitrogen fertility levels in soils can vary widely within short distances. There is growing interest in variable rate fertilization, especially on rolling topography. Field equipment, including air-seeders, should be evaluated for their potential in variable rate fertilization. Variability of available soil N with depth, and its relative availability compared to fertilizer N must also be addressed.

In general, N fertilizer management practices such as timing and placement of N fertilizers, and the need to adjust such practices depending on the N fertilizer form have been well researched. Firm recommendations are now needed for fall fertilization, recognizing the effect of soil moisture and temperature, economics and seedbed drying in spring versus stubble disturbance in fall. The preferred depth of fertilizer bands must also be better defined.

The current research with sideband, seedrow and nest placement of N fertilizer is vital, and should be continued with the goal of improved N FUE and reduced application equipment and energy cost.

The reader's attention is directed to Chapters 7, 9, 10, 11 and 12 for further comments on priority areas for further research in the general area of fertilizer and soil N.

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