

Problems using intensive sampling of soil moisture and nitrates to predict yield variation: Inferences for site-specific farming

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Abstract

Several conventional agronomic experiments in the Brown and Dark Brown soil zones, with emphasis on an experiment conducted on a knob and kettle landscape, were used to determine if intensive sampling for soil nitrates and water was useful for predicting yield variation and thereby represent a potential strategy for variable rate application of N fertilizer. Although there was a large range in soil water and, thus, crop water use in each of three years on the knob and kettle landscape, the durum grain yield was not strongly correlated with soil water at seeding. This was attributed to negative correlation between yield and soil water for areas having significant unexploited soil water from habitually poor crop growth combined with the generally positive correlation between soil water and yields for more productive areas of the field. There was a poor relationship between soil nitrate in the previous fall and grain yields. The response to N and water varied widely within the field and, thus, the response function for each small area needs to be known to successfully use a map of soil nitrates and water to predict optimum N fertilizer rates. Although the N supplying capability of the soil is an important factor determining the crop response to N for a specific field area, for medium-textured soils on glacio-lacustrine landscapes, there was not a positive correlation between potentially mineralizable N and crop yield. On rolling landscapes, crop yields were well correlated to surface organic carbon concentrations but this correlation was poor on gently undulating landscapes. Grain yields were relatively well correlated with yields the previous year on all landscapes providing drought years were excluded (during which yields were often negatively correlated with past yields). This suggests that a field yield map from a combine yield monitor and global positioning system will be useful for identifying areas of the field that should be managed similarly because they have the same general historical response to weather and fertilizer. Since lower yielding areas within a field often do not have lower crop water use than higher yielding areas, a potentially effective site specific management system would involve identifying and correcting (if possible) the yield-limiting factors in the less productive areas of the field. Intensive soil sampling to map water and N was not useful for predicting yield variation so that practice does not appear to be worthwhile for site-specific farming systems in the Brown soil zone of Saskatchewan.

Introduction

Traditionally, producers in the Brown and Dark Brown soil zone are highly concerned with maximizing the efficiency of cropping inputs such as fertilizer. This concern is largely based on the appreciable risk of drought these producers face each year. If a drought occurs, they may not be able to recoup the crop production costs. Consequently, to reduce the risk of financial hardship, producers will generally only fertilize up to rates that they are reasonably

certain will be profitable in favourable years. Frequently, some areas within a field yield well even with little fertilizer, further convincing the producer to minimize fertilization. Given the strong desire to maximize the return from fertilizer investment combined with the observation that the response to fertilizer is variable within the field, not surprisingly, producers in the Brown and Dark Brown soil zones are keenly interested in site-specific management (SSM) of fertilization. The promise of SSM is that fertilizer can be applied proportionally to the expected yield response for individual small land areas within a field and thereby maximize the economic returns from the fertilizer investment.

Water and N are the primary factors determining stubble crop yields in the Brown and Dark Brown soil zones. Campbell et al. (1997a) developed a regression model of stubble spring wheat yield involving 0-60 cm soil nitrates in the fall, fertilizer N, soil water, growing season precipitation, and growing degree days. The water and N terms (including their squares and products) accounted for 85% of the total variability in grain yields in the calibration data set (a further 1% of the total variability was explained by growing degree days). For the sites in the Brown and Dark Brown soil zones in Saskatchewan and Alberta for which the regression model was tested, it predicted 52 to 86% of the variability of grain yields. Thus, the relative importance of N and water supply in determining spring wheat yields appears to hold widely in those semiarid soil zones. Knowledge of soil water and soil N throughout the field would appear to be essential information to predict within-field yield variation.

Although the producer can not know the growing season precipitation at seeding time, the probability of a crop water use amount can be estimated from soil water in the spring and the probabilities of a growing season precipitation amount. By using the appropriate N-water-yield response function with a field map of soil water and nitrates, one can calculate the amount of N required in each small field area to achieve a set yield or net economic return goal for a given probability of crop water use. This process produces a field map of the required N fertilizer rates from the map of soil water and nitrates. Equipment using a Global Positioning System (GPS) then applies fertilizer N according to the rate map. Although this SSM system for N fertilizer is expensive because of the cost of the intensive soil sampling, with the anticipated development of on-the-go sensors for soil water and nitrates mounted on computerized fertilizer application equipment, this SSM system becomes a single operation and much more affordable (Hummel 1996).

The success of using intensive soil sampling for nutrient status for predicting the most profitable fertilization strategy has generally been poor in semiarid areas. The critical problem has been knowing the yield response function for each land management unit so the optimal fertilizer rate can be accurately estimated (Carr et al. 1991; Wibawa et al. 1993). A targeted soil sampling strategy that first delineates management units from crop growth and then applies fertilizer based on a limited sampling to determine the soil nutrient status of those units has shown promise (Long et al. 1995).

The primary objective of this paper was to analyze measurements of soil water and nitrates for an experiment conducted on a gently rolling knob and kettle landscape to evaluate the potential of intensive sampling for predicting yield variation in the Brown soil zone. The secondary objective was to explain the results for the above analyses using observations from three other agronomic experiments in the Brown and Dark Brown soil zones.

Materials and Methods

'Knob and Kettle' experiment

The experiment was conducted 20 km NNE of Swift Current on a gently rolling knob and kettle glacial till landscape (Ayres et al. 1985). The soils are Ardrill loam, predominantly Orthic Brown Chernozemic with a significant proportion of Calcareous Brown Chernozemic soils. The Calcareous subgroup soils are on knolls and divergent shoulders. Various Gleysolic (Gleyed Brown and Gleysols) soils were also present in poorly-drained depressions. Based on gleyed (i.e., low chroma) soil colours found in the upper 50 cm of soil during soil sampling we estimated 10% of the 6-ha study site contained Gleysolic soils. A large depression (slough) of 0.35 ha in the centre of the study site comprised the largest single area of the Gleysolic soils.

Before commencement of the study, the land had been in a long time crop-fallow rotation, except the central slough that had been cropped in most years when it had been trafficable in the spring. The entire study site had been cropped to spring wheat in 1988.

Details of the experiment can be found in McConkey et al. (1997a) so only aspects of the experiment related to this paper are included herein.

From fall 1988 to harvest 1989, there were 15 m by 15 m sampling sites located randomly throughout the 6-ha field. For that year, there were 65 Chernozemic and seven Gleysolic sampling sites. From fall 1989 thereafter, new consistent sampling sites were selected based on a approximate 20 x 35 m grid (the sites on the grid could be more easily identified during snow surveys when some site markers were buried in snow). The new sampling sites were a 10 m by 10 m area. The grid was modified where it intersected Gleysolic soils by moving the sampling site uphill until the site was at least 10 m from soils exhibiting gleyed colours or strong mottling in the upper 1.2 m soil depth. A sampling site was located near the centre of each area of Gleysolic soils. There were 78 Chernozemic and 11 Gleysolic sampling sites. We measured the slope and aspect at the centre of these sampling sites with a compass-inclinometer ("Pocket Transit", Kueffell and Esser Co., New York, NY). Of the Chernozemic sites, 37 had slopes less than 2%, 28 had slopes of 2% to 5%, and 13 had slopes of 5% to 10%. All the Gleysolic sites had slopes less than 2%. Soil organic carbon to 15 cm was determined from soil samples for the 1990-91 sites by dry combustion.

Prior to seeding fertilizer N was broadcast as ammonium nitrate at rates of 11, 28.40 kg N ha⁻¹ in 1989, 1990, and 1991, respectively, based on fall soil tests. The land was seeded to "Kyle" durum wheat (*Triticum turgidum* L.) at 87 kg ha⁻¹ by mid May using a disc harrow, then harrow-packed. Fertilizer P was applied with the seed at rate of 7 kg ha⁻¹.

About one week after seeding and one week after harvest, soil samples were taken at each sampling site to 120 cm in 20-cm increments from a 5-cm diameter soil core. Soil moisture was determined gravimetrically and volumetric water contents were calculated using bulk densities determined in fall 1988. Crop water use was defined as the difference in soil water between seeding and harvest sampling times plus the precipitation received between those dates. Precipitation from late April until harvest was measured with a recording rain gauge located at the west end of the study area.

In 1989, two 10 m by 1.4 m areas were harvested from each sampling site using a plot combine. In 1990, two 10 m by 1.4 m areas were harvested with a plot combine at the Chernozemic sites but four 1 m by 0.5 m samples were collected manually at the Gleysolic sites because of difficulty of feeding a precise area of the lodged crop at those sites into the plot combine. In 1991, due to trafficability problems caused by rainy weather and delayed maturity of the lodged crops at the Gleysolic sites, four 1 m by 0.5 m samples were taken by hand for grain yield at all sampling sites. Samples taken manually were threshed later with a stationary

plot combine.

The experiment compared both deep tillage practices and snow trapping in a randomized complete block design. These practices had relatively small effects on soil water and crop yields over the three years of the experiment (McConkey et al. 1997a) and so were ignored for the analyses in this paper. Correlation and regression analyses were done using the General Linear Models procedure in SAS version 6 (SAS Inst. Inc. 1990). For correlations involving both the 1989 sampling sites and for 1990-91 sites (e.g. correlation between 1989 and 1990 grain yields), the data was first kriged onto a common grid with GEO-EAS (EPA 1991) and then these estimates were analyzed.

"Ridge" experiment

The ridge experiment was conducted from 1987 to 1989 to determine the influence of landscape position on yield and water use of spring wheat. The ridge was singular feature on a relatively gently sloping (1-2% slopes) plain 3 km S of Swift Current, SK. Therefore, any runoff from the ridge did not collect at the toeslope of the ridge but rather drained across the plain. The soils graded from a Wood Mountain loam (Orthic and Calcareous Brown, medium-textured till parent material) at the summit to a Swinton loam at the toeslope (Orthic Brown, medium-textured loess over till parent material). The maximum slope of the ridge was 8% (Figure 1). Details of the experiment can be found in McConkey et al. (1997b).

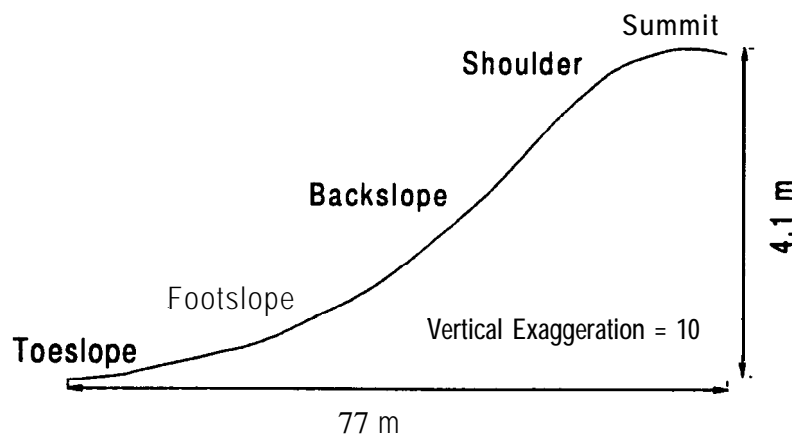


Figure 1. Slope positions for the "ridge" experiment.

"Brown Glacio-lacustrine" experiment

This experiment was conducted from 1983 to 1994 on Hatton fine sandy loam (Orthic Brown) at a site 15 km NW of Swift Current, SK. The landscape was gently undulating and the parent material was medium- to coarse-textured glacio-lacustrine deposits. This experiment evaluated the agronomic performance of conventional-, minimum- and no-tillage production systems. Details of the experiment can be found in McConkey et al. (1996). For this paper we only considered the continuous durum wheat plots. There were nine of these 15 by 30 m plots in the experiment, arranged randomly over the length of the 30 x 405 m field. Although there have

been no consistent or large differences between tillage systems for continuous durum (McConkey et al. 1996), we removed the linear effect of the tillage systems before analysis.

“Dark Brown Glacio-lacustrine” experiment

This experiment refers to the initial characterization for an alternative cropping systems study. The study is located on Elstow loam (Orthic Dark Brown) at the Agriculture and Agri-Food Canada Scott Research Farm. The landscape is gently undulating and the parent material is medium-textured glacio-lacustrine deposits. In this paper we are using the results of the 1994-95 spatial characterization of the field before the cropping systems study was initiated (Selles et al. 1996). Prior to the characterization, the 20-ha field had been farmed uniformly for many years using conventional production practices for the area.

Results and Discussion

Variability

In each year, there was a wide range in total soil water, water use, soil nitrates, soil P, and durum grain yield (Table 1). All the distributions were positively skewed as indicated by the arithmetic mean being closer to the minimum than the maximum value. Water use was generally above average for the Brown soil zone reflecting the favourable growing season precipitation (Table 2).

The variation in soil nutrients is similar to that reported by Franzen et al. (1996) for one field in North Dakota but somewhat larger than that reported in other fields in North Dakota (Wibawa et al. 1993), Montana (Carr et al. 1991) and Alberta (Penney et al. 1996).

The positively skewed soil nutrient frequency distributions tend to cause the nutrient concentration of a composite soil sample to overestimate the appropriate concentration for a large proportion of the field (Penney et al. 1996). This arises whenever a subsample from an area with exceptionally high nutrient concentration is included in the composite sample.

Soil Water

The correlation between yield and total soil water for the “knob and kettle” experiment was surprisingly poor (Table 3). The poorly drained Gleysolic soils were generally higher yielding and had more total soil water (partly due to higher clay content) than the upland Chernozemic soils (McConkey et al. 1997). Considering only the Chernozemic soils, the correlation between yield and soil water was even lower (Table 3).

The results from “ridge” experiment probably explains why there was not a stronger positive correlation with the potential water supply. In that experiment McConkey et al. (1997b) found that higher soil water contents were associated with upper slope positions that had lower yields. They related this effect as a residual effect of long-term wheat-fallow rotation. Within that rotation, they speculated that crop water use was lower with lower yielding crops at the upper slope positions. Although crop water use was more proportional to available soil water under annual cropping, yields in the non-drought years of 1987 and 1989 (Figure 2) were still lower at the upper slope positions. Thus, there was a strong negative correlation between available soil water and crop yield (Table 4). In the drought year of 1988, available soil water appeared to be the dominant factor that determined crop yield so yields were higher in the upper

Table 1. Variation in selected attributes by year for the 'knob and kettle' experiment

Attribute	1989			1990			1991		
	min.	mean	max.	min.	mean	max.	min.	mean	max.
O-1.2-m water at seeding (mm)	131	228	458	148	233	457	202	300	468
O-1.2-m N-NO ₃ (kg ha ⁻¹)	19	68	244	12	65	357	17	44	488
0-0.3-m NaHCO ₃ -P (kg ha ⁻¹)	27	48	149	5	44	131	6	48	184
water USC (mm)	237	321	453	293	395	536	342	452	559
grain yield (kg ha ⁻¹)	1202	2095	4460	1215	2562	5293	1580	2972	4911

Table 2. Precipitation for the "knob and kettle" experiment.

Crop Year	Period	
	Sep (prev.) to Apr ^z (mm)	May to Aug ^y (mm)
1989	151	300
1990	140	343
1991	129	368
Long-Term Mean ^x	150	207

^z Measured at the Agriculture and Agri-Food Canada Research Centre, 22 km SSE of the study site in the fall and winter prior to seeding.

^y Measured at the study site.

^x 1886-1988 for Swift Current, SK

slope positions producing a positive water-yield correlation.

A similar effect probably existed for the “knob and kettle” experiment. Some locations with higher soil water content were probably also associated with historically poor crop growth. As evidence of this effect, excluding 1991 when the soil was moist everywhere at harvest due to late season rains, grain yields tended to be lower where soil water at harvest was greatest (mean correlation coefficient between yield and harvest soil water of -0.17). However, other locations with high soil water content probably represented areas where topography causes water accumulation that increases yield potential. The co-existence of these two opposing trends would explain the comparatively low correlation between soil water and crop yield. The areas exhibiting a negative correlation of yield with soil water will probably lessen as the duration of annual cropping increases (McConkey et al. 1997b).

Available soil water typically varied over by 30 to 50 mm among the continuous durum plots within the “Brown glacio-lacustrine” experiment (data not shown). The mean annual correlation between yield and soil water was -0.25, probably reflecting the general pattern of low-yielding plots having more residual available water than higher yielding plots.

Adding to the difficulty of using soil water to predict yield variation are varying soil textures and bulk densities within the field. For example, in the “ridge” experiment, 0-1.2-m soil water content at the assumed 4.0 MPa wilting point ranged from 158 mm for the finer and denser soils at the ridge summit to 126 mm for the more medium-textured and less dense soils at the toeslope position (McConkey et al. 1997b). The 4.0 MPa water content over the 0-1.2-m depth was 242 mm for the Gleysolic soils and 152 mm for the Chernozemic soils within the “knob and kettle” experiment, largely reflecting difference in average clay content between the soils (McConkey et al. 1997a). Unless the expensive measurement of the lower limit of water availability is conducted for each small area of the field, total soil water will probably vary much more than plant-available soil water in fields with varying soils.

Nitrogen

For the “knob and kettle” experiment, the correlation between soil nitrates in the fall and yields was poor (mean annual correlation coefficient of 0.35). Including water use in the N-yield relationship, by dividing water use into three classes (237 to 350 mm, 350 to 450 mm, and 450 to 559 mm), increased the correlation between N supply (soil nitrates + fertilizer N) and yields (Figure 3). This confirms the observation of Kachanoski et al. (1985) that both water and N must be considered together to estimate yield response on rolling soil landscapes.

Losses of nitrates due to denitrification and leaching can be large in rolling soil landscapes (Farrell et al. 1996). Therefore, the nitrates measured in the fall may not accurately represent the mineral soil N that was readily available for crop uptake. These losses would be greatest in the depressional Gleysolic soils that accumulated runoff (Farrell et al. 1996). Thus, the fall soil sampling may have overestimated N supply in those soils. The 3-yr mean grain yield and fall 0-1.2-m soil nitrates were 352 t and 126 kg ha⁻¹, respectively, for the Gleysolic soils compared with 244 t and 52 kg ha⁻¹, respectively, for the Chernozemic soils. If nitrate losses between fall soil sampling and crop uptake were large on the Gleysolic soils, this would reduce the apparent yield response we observed to N supply for conditions of high water use (Figure 3).

The quadratic least-squares regression of yield to N supply for three water use ranges all explained a relatively low proportion of the yield variability (Figure 3). Including 0-0.15-m soil NaHCO₃-P measured in the fall into these regression models did not significantly increase the fit of measured to predicted yields (data not shown). This was probably because soil P content was relatively high (Table 1) so a strong yield response to P was not expected and because the effect of soil P could not be separated from that of soil nitrates since these two nutrients were positively

Table 3. Mean annual correlation coefficient between grain yield and total O-1.2-m soil water for the “knob and kettle” experiment..

Areas	r
Chernozemic and Gleysolic	0.36
Chernozemic only	0.21

Table 4. Correlation coefficient between grain yield and O-1.2-m available soil water for the “ridge” experiment.

Year	r
1987	-0.997
1988	0.482
1989	-0.751

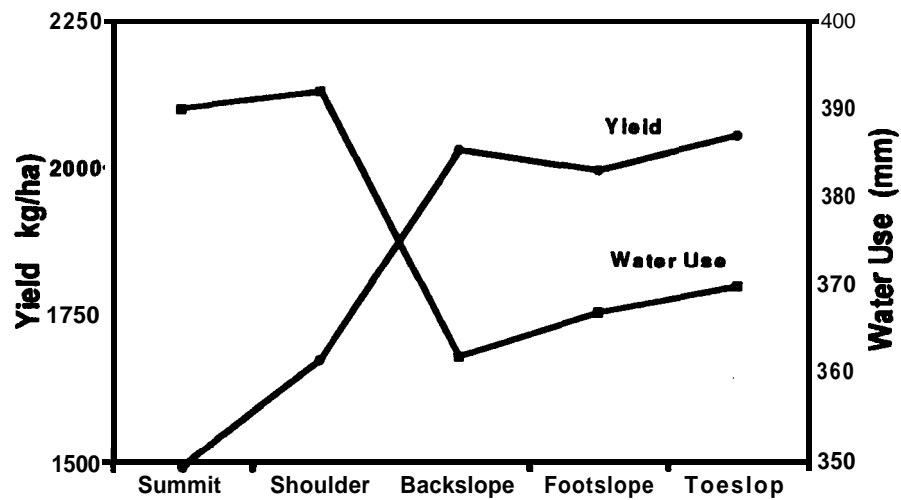


Figure 2. Water use and yield for “ridge” experiment in 1989 [slope position effect was significant ($P < 0.05$) for both yield and water use]

correlated (mean correlation coefficient of 0.48). The apparent response to N supply for the two higher water USC classes followed classical behavior of decreasing response as N supply increased. However, the apparent response function for water use less than 350 mm was essentially flat with regard to N supply up to about 200 kg ha⁻¹. This is probably not necessarily an appropriate N response function over the long term but dramatizes that there are varying responses to N supply among specific small land areas so that aggregate response to N supply across the field can be much different than expected.

Similar problems using soil nitrates to predict the variation in yields existed on the more level landscapes. For example, within the "Brown glacio-lacustrine" experiment, two plots that had been managed identically (no-till) from 1983 to 1994 showed large, almost consistent differences in durum yields (Figure 4). However, based on soil nitrates measured in the spring just prior to seeding, the plots had the same yield potential.

In developing nutrient-yield response functions for fertilizer recommendations based on soil nutrient testing, agronomists have long recognized that it is infeasible to have a response function for every small land area within one field in one year. Frequently, one individual replicate in a conventional replicated fertilizer rate experiment has unexpectedly low yields relative to nutrient supply in one year while another replicate has unexpectedly high yields in that same year. The variability in response between specific small land areas (i.e. individual replicates) becomes much larger when many soil types, fields, and years are involved, as is the case in the data sets used to develop nutrient-water-yield response functions for general use in Saskatchewan. The general-use nutrient-water-yield response functions used for soil-test recommendations often provide poor estimates of the optimal fertilizer rate for specific small land areas (i.e. one replicate) within the data set used in its development. Therefore, when applying the general response function to a specific small land area within one field, we can not necessarily assume that the general function will predict the optimal fertilizer rate for that specific area. The relatively poor performance of N supply to predict yield variation in the "knob and kettle" experiment (Figure 3) shows that specific areas had a wide range of yield responses to N. To develop a completely successful site-specific management system for fertilizer application based on mapping the soil nutrient and water status, it will be necessary to know the nutrient-water-yield response function for every small area within the field (Carr et al. 1991; Wibawa et al. 1993). Quantifying the response function for every small land area is not feasible for low-value crops such as wheat. However, without these response functions, it will not be worthwhile to undertake an intensive soil sampling strategy to map the soil moisture or nutrient status.

As discussed above, the general nutrient-water-yield response function used for making fertilizer recommendations have been developed from data for many small land areas exhibiting a wide range of nutrient responses. Thus, there is no reason to necessarily assume that response function will not predict an optimal uniform fertilizer rate for a field that also has many small land areas exhibiting a wide range of nutrient-yield responses. Consequently, there is a significant challenge to develop a SSM system for fertilization that consistently provides better net economic returns than the simple system of applying a uniform fertilizer rate based on the nutrients in a composite field soil sample.

Since grain N was not measured for the "knob and kettle" experiment, we estimated this from the regression model of Campbell et al (1997b). Predicted grain N varied from 15 to 25 g kg⁻¹. Grain yield is the most important factor in N uptake in grain (Clarke et al. 1990) so the cumulative estimated 1989-91 net N removal (Figure 5) showed a similar pattern as cumulative 1989-91 grain yield (Figure 6). Because of the favourable growing season precipitation and resulting above-average grain yields, all areas of the field were estimated to have had more N removed as grain than added as fertilizer. The highest yielding areas must have had good N

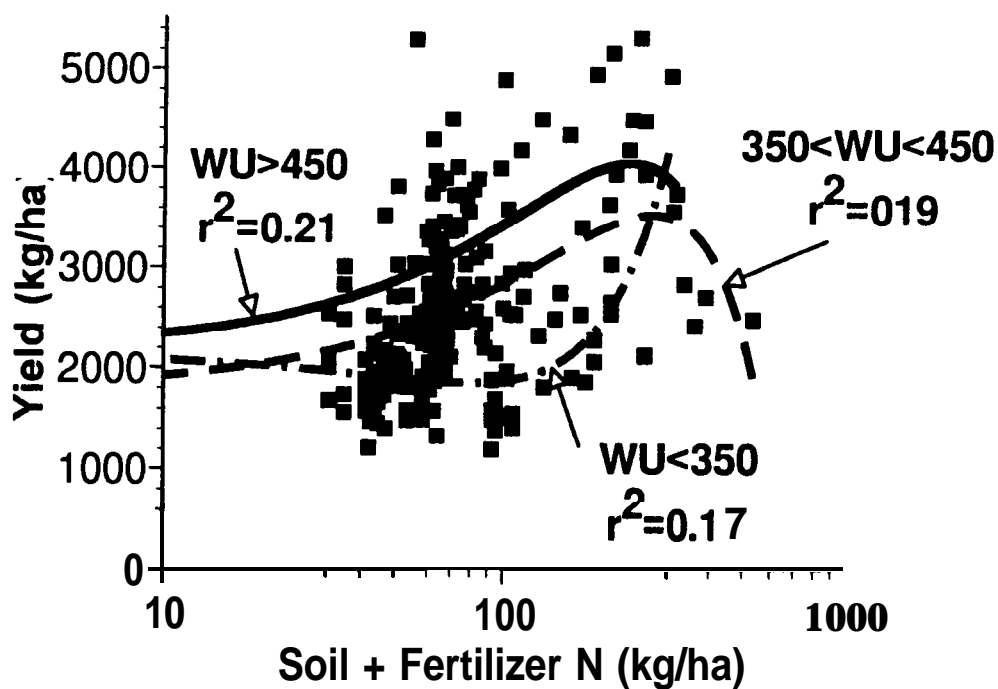


Figure 3. Quadratic least-squares regression of durum grain yield to N supply (fall soil nitrates plus fertilizer N) for three water use ranges.

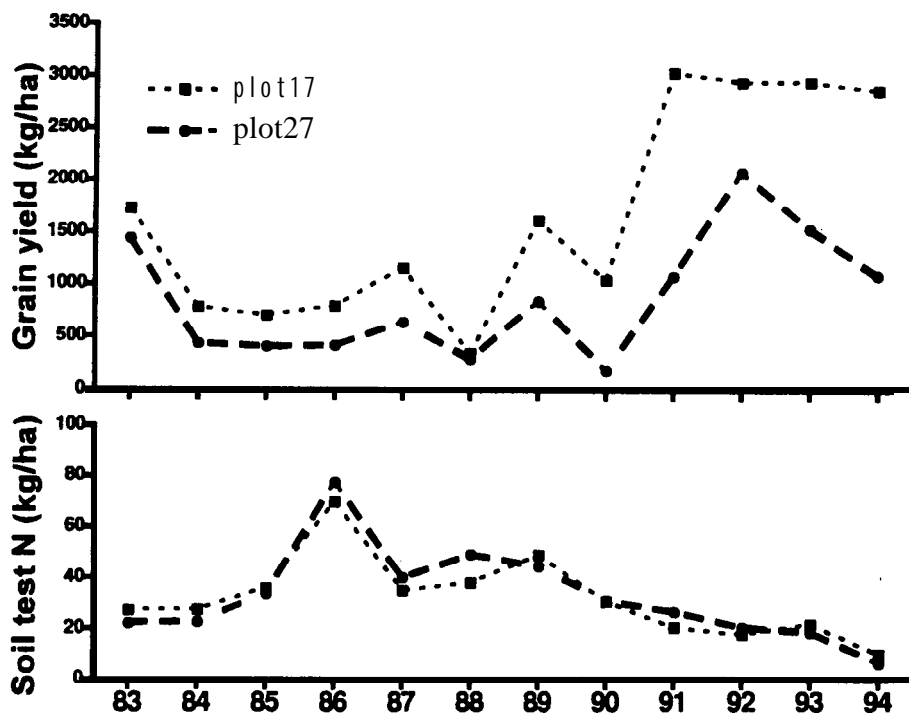


Figure 4. Durum grain yield and spring 0-0.6-m soil nitrates for two identically managed no-till continuous durum plots within the "Brown glacio-lacustrine" experiment.

supplying capability to have the measured yields. Clearly, the soil N supplying capability must be considered in a SSM system.

The soil N-supplying capability can be estimated from potentially mineralizable N (**N_{min}**), a laboratory procedure (Campbell et al. 1993). **N_{min}** has been closely related to yield potential (Campbell et al. 1996). However, there was no strong positive correlations between **N_{min}** of soil sampled in April 1990 and 1990 grain yields for the “Brown glacio-lacustrine” experiment or between **N_{min}** of soil sampled in spring 1995 and the 1994 yield of well-fertilized barley for the “Dark Brown glacio-lacustrine” experiment (Table 5). In fact, the relationship for the “Brown glacio-lacustrine” was highly negative correlated. As shown by the behaviour of plots 17 and 27, the lower yields of some small land areas was not reflected by soil nitrate levels (Figure 4). Therefore, when fertilizer was applied to soil-test recommendations, the lower-yielding areas had more N added as fertilizer than was removed in grain (Figure 7). Presumably, some of the unused fertilizer N became labile organic N that was mineralized during the **N_{min}** procedure. This would explain the inverse relation between **N_{min}** and yield. For the “Dark Brown glacio-lacustrine” experiment we suspect that the low correlation between yield and **N_{min}** reflected a pattern analogous to the low correlation between yield and soil water for the “knob and kettle” experiment. Some areas of inherently low crop yield potential probably had high **N_{min}** because crop had not thoroughly exploited the N supply while, in other areas of higher yield potential, yield was positively correlated with **N_{min}**. Thus, over the field, these two opposing trends produced a weak correlation between **N_{min}** and crop yield.

Relationship of yield to other attributes.

There was a generally good correlation between the grain **yield** in the current year and the grain yield in the previous year (Table 6). However, in drought years, (1988 for the “ridge” experiment and 1984, 1985, and 1988 for “Brown glacio-lacustrine” experiment), the correlation was near zero or negative. This is probably related to the general effect of lower-yielding areas having more residual soil water. Use of this residual water by the crop can increase the yield of the historically lower yielding areas in a drought year (McConkey et al. 1997b). The good correlation **between** yields in different years may be a feature of semiarid areas as consistent correlations between years has not been observed in some subhumid areas (Lamb et al. 1995).

Since relative yields are comparable across years, areas of similar yields likely have a similar general response to weather and fertilizer. This indicates that a yield map from a combine yield monitor and GPS is a potentially valuable tool for identifying land management units within **a field**. Of course, to use a yield map to identify management units for fertilization, the effect of weeds, diseases, and insects must be quantified and considered (these factors were judged to be relatively unimportant in the experiments discussed in this paper). Based on our results, yield mapping would be useful to identify land management units in all soil landscapes.

For the experiments conducted on rolling land (“knob and kettle” and “ridge”), there was a relatively good correlation between surface organic C concentrations and crop yields (Table 6). However, on the gently undulating glacio-lacustrine landscapes, there was a poor correlation. Since it is relatively inexpensive to estimate relative organic carbon levels from soil reflectance of different **wavelengths, including visible** wavelengths (i.e. black and white aerial photographs of bare soil), reflectance-based identification of land management units is promising for rolling land.

Inferences for site-specific management of fertilization

In the Brown soil zone, low yielding areas of the field are often not areas of low available

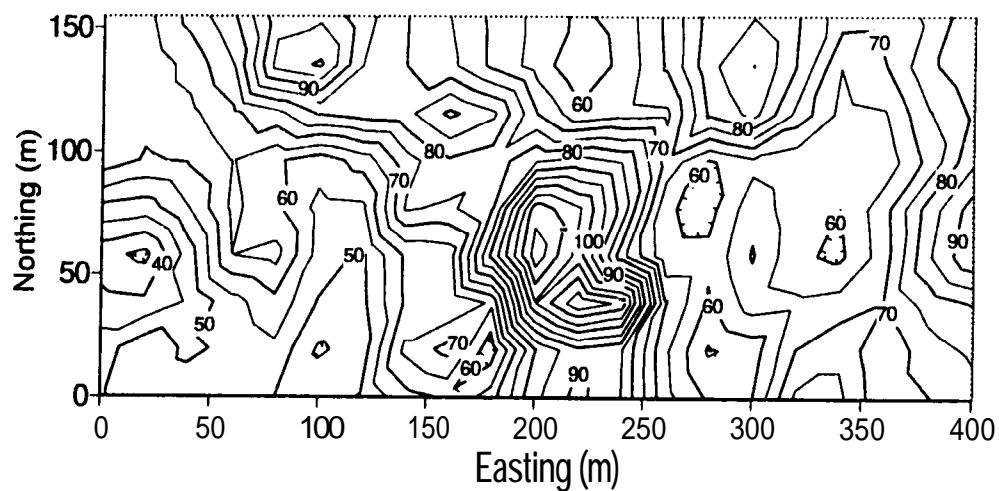


Figure 5. Estimated cumulative 1989-9 1 N removal in grain less fertilizer N additions (kg ha^{-1}).

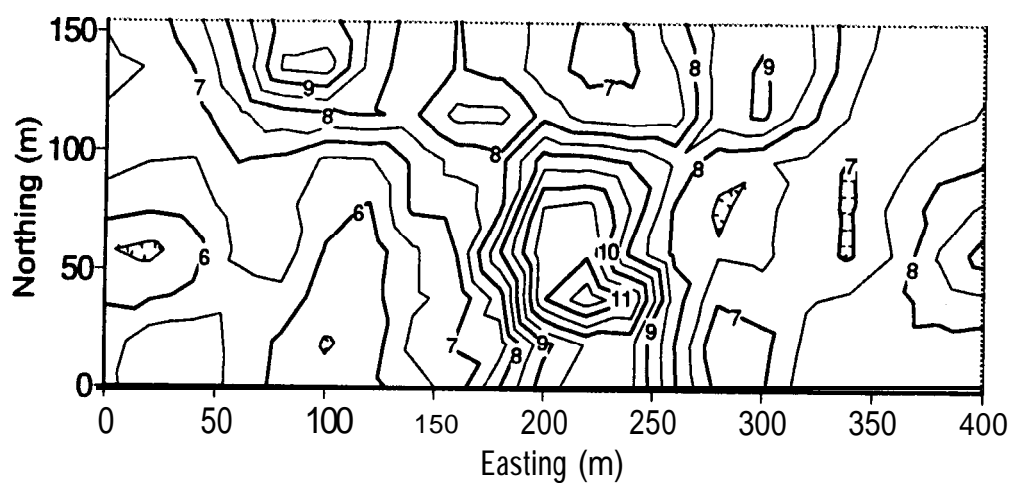


Figure 6. Cumulative 1989-1 99 1 grain yield (Mg ha^{-1}).

Table 5. Correlation coefficients between grain yield and potentially mineralizable N.

Experiment	r
"Brown glacio-lacustrine"	-0.89
"Dark Brown glacio-lacustrine"	0.26

Table 6. **Mean correlation coefficients** between grain yield and selected attributes (excluding drought years).

Experiment (years)	Yield in the past year	Surface organic C
‘Knob and kettle’ (1989-91)	0.49	0.55
“Ridge” (1987,1989)	0.82	0.77
“Brown glacio-lacustrine” (1986-87, 1989-94)	0.68	0.11
“Dark Brown glacio-lacustrine” (1994)	—	0.06

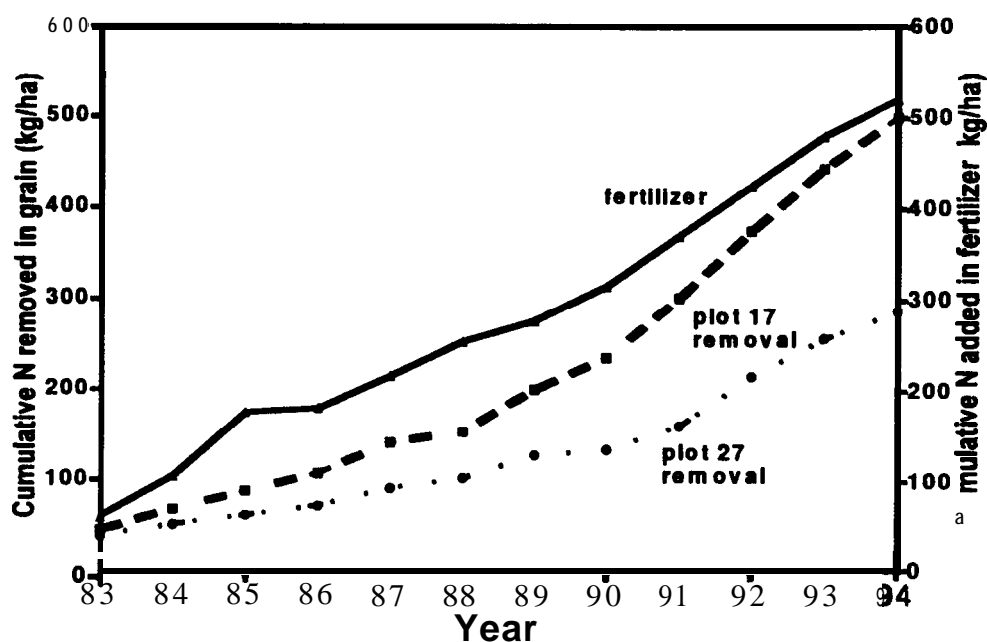


Figure 7. Cumulative N removal in grain and N added in fertilizer for two identically managed no-till continuous durum plots within the “Brown glacio-lacustrine” experiment.

soil water or crop water use. Therefore, there would appear to be a large potential to raise yields in the lower yielding areas by increasing the crop water use efficiencies to those of the higher yielding areas. A promising approach for SSM would be to identify the lower yielding areas and then determine the factors causing the lower yields. If the factors were primarily macro- or micro-nutrients, the limiting nutrients could be selectively applied to the lower yielding areas. Hopefully, similar yield limiting factors would exist in lower yielding areas of other fields having the same soil complexes and parent materials. Therefore, the cost of researching the yield-limiting factors could be justified as a public investment by its potential application over a much larger land area than one field or farm.

On rolling soil landscapes, the lower yielding zone may also correspond to areas of similar topographical position or organic carbon content thereby simplifying the identification of which areas have similar responses to fertilizer. For example, Kachanoski et al. (1985) and Jowkin and Schoenau (1996) concluded that there was likely to be better yield response to N supply in footslope positions than upper slope positions. On more level fields, yield maps from GPS-based combine yield monitors or aerial colour infrared images of growing crops would be low-cost methods for identifying areas of similar yield or growth potential that may also have similar crop-nutrient response functions.

Although the results from the experiments indicated that intensive soil sampling of a field is not likely to be worthwhile, targeted soil sampling by land management unit may have merit. Long et al. (1995) conducted a limited soil sampling of individual field areas having similar relative crop growth. When fertilizer nutrients were applied according to soil-test recommendations for those specific field areas, this system provided higher net economic returns than a single uniform nutrient application rate across the field.

Conclusions

Stubble durum grain yield, soil nitrates in the fall, and soil water at seeding and harvest were measured over three years on a knob and kettle landscape. Yields were weakly correlated with soil water alone, soil nitrates alone, or N supply for different water use ranges. Since low yields often could not be related to low water use, there would appear to be a large potential to increase crop yields on a field basis if the factor(s) limiting yields could be identified and corrected on the lower-yielding areas. Because we observed a wide range of yields for a given N supply or total water use, without good knowledge of the nutrient-water-yield response function throughout the field, it would not appear worthwhile to undertake intensive soil sampling to map water and nutrients in the field. A promising site-specific management system for fertilization may involve adjusting rates of fertilizer macro- and micro-nutrients for individual land management units identified from past yields.

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