PRECISION AGRICULTURE: SPATIAL AND TEMPORAL VARIABILITY OF SOIL WATER, SOIL NITROGEN AND PLANT CROP RESPONSE

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SYNOPSIS. The spatial and temporal variability of soil water and nitrogen supply capabilities, as well as the spatial and temporal changes in plant nitrogen uptake on the field and farm levels, require different fertilizer management strategies to obtain economically and ecologically reasonable yields. Site-specific crop management aims at optimizing agriculture production by managing both the crop and the soil with an eye toward the different conditions found in each field.

This report focuses on recent developments to characterize the spatial and temporal variability of soil water, soil nitrogen and plant nitrogen uptake more efficiently, with the aim being to optimize nitrogen input relative to the site-specific yield potential. Site-specific crop management approaches have been designed and tested to optimize agricultural production; the methods presented here allow for a site-specific targeted nitrogen application. Results show that they can simultaneously benefit both the farmer and the environment.
Key words: nitrate test, plant available water, remote sensing, sensor, site-specific, soil water availability

INTRODUCTION

Biomass production is driven largely by nitrogen and water supply, which are the most important factors limiting plant growth, development and yield. Although improvements in nitrogen use efficiency have been realized, considerable room for further improvement remains, yielding both economic and environmental advantages. Because nitrogen fertilization can account for a significant part of total production expenses, the rational management of such high-cost input can have a great impact on the profitability of crop production. The recent, dramatic increases in nitrogen prices therefore represent strong incentives to optimize nitrogen use. In addition, the potential for environmental impacts has to be considered because nitrogen application rates in excess of crop requirements can contribute to increased nitrate levels in the soil profile, thereby increasing the risk of nitrate leaching from agricultural lands to surface and ground waters. Moreover, nitrate can also be lost to the atmosphere through denitrification. Enhanced nitrogen use efficiency would both reduce undesirable leaching losses and abate gaseous losses.

The last decade has been characterized as the driest period on record. As such, water shortage has become a major issue worldwide, albeit its regional impact varies significantly. Although water shortage seems to be less of a general issue in more temperate regions, it operates at a more local scale. Annual yield variability is clearly related to the annual water supply and its distribution. Moreover, water availability can vary both among and within fields.

Recommendations for N fertilization in grain crops have always been a challenge because of the difficulty in predicting the amount of nitrogen mineralized from the soil organic matter pool during the growing season and because of the high nitrate mobility in the soil profile. In addition, large spatial differences in the nitrate content and N supply capability of the soil and in the N status of plants can also exist in the field. In most cases, the application of N fertilizers is carried out without taking soil and crop spatial variability into consideration. Thus, N fertilizers are applied in a uniform manner over a given field, using a single N rate based on the average needs of the field as a whole. However, the reality is that many fields consist of two or more soil types with different N and water supply capabilities and different crop yield potentials that require different fertilizer management to obtain economically and ecologically reasonable yields. In such cases, a uniform N management can cause some sites within the field to be either under- or over-fertilized. Such discrepancies can become even more aggravated in light of many N-recommendation systems being based primarily on yield expectation (Olfs et al., 2005). Optimum N-rates will not be constant for a specific crop, but vary annually with further differences being observed among cultivars (MacKenzie and Taureau, 1997). Again, differences also exist among and within individual fields (Welsh et al. 2003).

This report focuses on recent developments (primarily proximal and remote sensing systems) to characterize the spatial and temporal variability of soil water, soil nitrogen and plant nitrogen uptake more efficiently, with the aim being to optimize nitrogen input relative to the site-specific yield potential.The spatial and temporal variability of soil nitrate is first documented and the consequences for optimized sampling strategies are described. A recently developed quick-test procedure allows for immediate on-site testing of the soil nitrate content. The interactive effects of water and nitrogen are described as factors contributing to yield variability. Finally, new methods to detect the spatial soil variability are introduced, with particular emphasis on proximal sensing as a tool to detect the spatially variable nitrogen uptake non-destructively. Based on all these methods, optimized site-specific strategies that were tested in multi-locational and multi-year investigations are used as examples to illustrate map – and plant-based strategies to optimize nitrogen application.

RESULTS

Spatial and temporal variability of soil nitrogen

Spatial variability of soil properties as a result of abiotic and biotic factors, as well as of considerable small-scale variations in topography and climate, has long been recognized. With the introduction of statistical analyses and global positioning systems, systematic recording and analysis of soil properties has become possible. The inherent high variability of inorganic and organic nitrogen in soils has been illustrated repeatedly (e.g. Van Meirvenne and Hofman, 1989). Results show that nitrogen varies considerably and more or less comparably from small (1 m^2; Raun et al., 2002; Solie et al., 1999) to larger scales (1 ha to tens of hectares; Reuss et al., 1977; Schmidhalter et al. 1992; Giebel et al., 2006), with few differences observed irrespective of the form and availability of nitrogen (e.g., total nitrogen, organic nitrogen, mineral nitrogen). Coefficients of variation of between 30-60% have been described frequently, irrespective of the scale (Reuss et al., 1977; Schmidhalter et al., 1992). Nitrogen tends to be distributed log-normally rather than normally in the soil and the geostatistical ranges characterizing the spatial dependence tend to be larger than 20 m, reaching up to several hundred meters on occasion. Within a given season, slight increases in variation were observed, probably as a result of increased mineralization (Schmidhalter et al., 1992).

Standardized sampling protocols cannot be developed for available nitrogen because of its inconsistent levels, with changes being apparent from year to year and from crop to crop. From this point of view, the application of geostatistical analyses, while useful, remains elusive. Even so, it remains worthwhile to consider the number of representative samples that account for the spatial and temporal variability. Recommendations for assessing soil mineral nitrogen in Germany suggest that about 16 samples per field be composited to obtain a representative sample. However, taking soil samples is extremely laborious and time consuming. Instead, detailed geostatistical analyses based on a large number of samples per field suggest that the mean values can be estimated with a reduced number of samples with little decrease in the precision of the estimation (Schmidhalter et al., 1992). Application of this result would allow the sampling of a higher number of fields with a reduced number of samples, with the expectation of a stronger basis for N-fertilizer recommendations that will be not only economically, but also environmentally advantageous. Although the number of analyses required would be increased, advances in soil nitrate analysis with respect to its costs and speed means that this step is no longer the limiting one. The introduction of much simplified on-site testing procedures means that soil nitrate can now be analyzed very simply and cheaply on site (Schmidhalter, 2005); combining such procedures with the recent introduction of a very simplified and inexpensive reflectometer (e.g. Reflectometer RQeasy, Cat. No. 1.17960.0001, E. Merck, Darmstadt, Germany) promises additional, substantial progress. Furthermore, the excellent agreement between the developed quick-test procedures and the standard laboratory procedure will allow the replacement of the latter without any loss of precision. Altogether, because these on-farm procedures not only allow more frequent determinations, but also ones that are cheaper and deliver the result in a much shorter time, they have the potential to deliver significant economic savings for farmers and benefits for the environment.

Crop response to water and nitrogen

As is the case for nitrogen, plant available soil water varies frequently as a consequence of the variability of soil texture and is the norm rather than the exception in most fields. Precipitation variability is often no less important than that in soil, and its effect on the crop yield can often be even more considerable than that of spatial variability.In many areas of the world, available soil water and precipitation or irrigation amount and distribution are among the primary factors determining yields of crops such as winter wheat (Stephens and Lyons, 1998; Nielsen and Halvorson, 1991). The optimum fertilizer N level is related to the amount, timing and kind of water supply (Eck, 1988). Black (1982) showed that, on loamy soil in Montana, the efficiency by which spring wheat used available water supplies (stored soil water and growing-season precipitation) to produce grain was influenced markedly by fertilization. In particular, more N was needed for maximum yield response as the amount of growing-season rainfall increased.

Site-specific agriculture aims at optimizing inputs on the field and farm levels, and thus can benefit both the farmer (in terms of net return) and the environment (through lower emission levels). The response of grain yield to nitrogen application likely varies in a site-specific manner. To evaluate the interaction between plant available soil water, precipitation (or irrigation) and nitrogen, fertilization experiments were conducted over two consecutive years with winter wheat with two different N fertilizer treatments (180 N kg ha^{-1} and 120 N kg ha^{-1}) and three different water supply treatments (stress by rain-sheltering, irrigation and rain-fed only) on sites of different plant available soil water. Among the three factors (i.e. site, precipitation and N fertilization), site was the most important one influencing variability in grain yield, whereas precipitation, and in particular its distribution during the growing season, influenced the overall yield level in a given year. Increased N fertilization generally increased yield, but its efficiency was low on lower yielding sites such as sandy soils if climatic conditions were unfavourable, thereby advocating reduced N fertilization application on sites of lower plant available soil water. This result also underscores the importance on such sites of sufficient water supply for efficient N use as already reported by others (Eck, 1988). For the maximum benefit, crop management should consider annual variability in yield in addition to soil conditions, and site-specific N fertilization should be adapted to the actual plant growth.

Non-destructive methods to determine soil properties

It is generally recognized that mapping represents an important tool to detect management zones. Such information can be obtained on the ground by means of yield mapping systems (Blackmore et al., 2003). But, because yield maps represent the amalgamated information of several factors, they do not always permit the determination of potential limiting factors and can also vary from year to year. Although not as accurate, similar information to that provided by yield maps can also be obtained by proximal sensing (Schmidhalter et al., 2001) or aerial remote sensing based on reflectance measurements. The latter is a particularly interesting method with the ability to cover large areas. More importantly, sensing soil properties directly allows for a more causal inference of limiting factors and thus for a more targeted management strategy. Analyses of both within and between field variability in plant growth have suggested those soil properties that decisively influence final yield. In particular, available soil water is closely related to the final yield. Similarly, site-specific yield potentials can be influenced by the amount of organic matter in the soil and especially the nitrogen content among other properties.

However, the lack of high spatial resolution topsoil data is a serious limitation to the establishment of site-specific soil and crop management. Simple methods to detect important soil properties would facilitate the development of optimized management strategies. With the recent advance of non-destructive proximal or remote sensing techniques, this goal of characterizing field-site characteristics using high spatial resolution soil data seems to be within reach. Near infrared spectroscopy (NIRS) represents a powerful technique to detect soil texture, organic matter and soil nitrogen content non-destructively. It is based on the observation that relationships between soil spectral reflectance data and both organic matter characteristics (Reeves et al., 2002; Udelhoven et al., 2003) and soil texture (Ben-Dor et al., 2002; Cozzolino and Morón, 2003) exist, with further comprehensive evidence from the literature that there is a close relationship between reflectance measurements (either from the lab or field based) and other important soil characteristics. It is expected that NIRS will make a strong addition to and partly replace destructive physical or chemical measurements of soil properties, especially in light of the further advances in instrumentation that are expected. Even so, more general region-wide calibration sets have to be developed and soil-specific algorithms will also likely be advantageous.

Recently, the potential to derive the spatial variability of within-field topsoil texture and organic matter was studied using airborne hyper spectral imagery to develop improved fine-scale soil mapping procedures (Selige et al., 2006). The percentage sand, clay, organic carbon and total nitrogen content could be predicted quantitatively by a multivariate calibration approach using either partial least-square regression (PLSR) or multiple linear regression (MLR). Moreover, the different topsoil parameters could also be determined simultaneously from the spectral signature contained in the single hyper spectral image given that they are represented by varying combinations of wavebands across the spectra. As such, the methodology appears to provide a means of simultaneously estimating topsoil organic matter and texture in a rapid and non-destructive manner, whilst avoiding the spatial accuracy problems associated with spatial interpolation. Further evaluation of this approach as well as the development of generalized or soil-specific algorithms will be highly desirable. For ground-based work, the development of robust field NIRS systems could advance the spatial resolution greatly as well as being coupled to high-performance aerial detection of important soil properties in the future. The high spatial resolution data thus obtained either from laboratory measurements or from ground or remote sensing data can be used to monitor and better understand the influence of management and land use practices on soil organic matter composition and content. This information can then be incorporated in optimized management decisions.

Organic matter accumulates primarily in the plough layer of the topsoil. Although plants absorb a significant amount of water from the top layer of the rooting zone, the whole rooting depth is relevant for water uptake. Biomass production and transpiration/evapotranspiration are related to each other linearly under water deficit conditions. From this general relationship, it can be concluded that biomass production is related to the available soil water, particularly under water deficit conditions. Furthermore, because differences in evapotranspiration can be reflected in varying canopy temperatures of crop stands, a feed-forward soil-crop response mechanism would allow the plant available water capacity to be inferred from the surface temperature of sensitive crops such as winter wheat during specific, so called 'bio-indicative', crop development stages. Surface temperatures recorded by remotely sensed thermography could thus allow the pattern of plant available water in fields to be detected (Selige and Schmidhalter, 2001). As a result, it is now feasible to produce precise and spatially detailed maps of plant available water capacity and, consequently, the site-specific yield potential of individual fields even at the sub-field level (Selige and Schmidhalter, 2006, in prep). A site-specific crop management system that is based on such maps would enable crop growers to adjust nitrogen optimally by attuning crop demand to soil productivity.

Non-destructive methods to sense nitrogen uptake in plants

Because of the high temporal and spatial variability of N in soil, fertilizing strategies based on the actual detection of crop N status rather than estimating soil N supply should be more successful in improving N fertilizer use efficiency (Ferguson et al., 2002). According to Raun et al. (1998), indirect, non-destructive sensor-based methods of plant analyses could replace many of the chemistry-based testing methods that are used today.

Several plant and soil diagnostic parameters based on destructive plant sampling and analysis have been used for N fertilizer management and as guidelines for N rate recommendations. The parameters employed most frequently are total nitrogen (Kennedy et al., 2002) and N-NO_3^- concentration in the shoots (Fox et al., 2001), N uptake by the canopy, and leaf chlorophyll content (Schepers et al., 1992). However, main limitation of these destructive sampling methods is that they are highly labour-intensive with respect to the need for plant sampling and processing. Moreover, a time delay often exists between the time of sampling and obtaining the analysis result.The methods used currently to determine N needs in the field (e.g. plant analysis, chlorophyll meter) are not suitable for on-line monitoring of the nitrogen status of crops if one takes into account the number of samples necessary to achieve a reliable result and the time needed for such evaluations. For instance, although the chlorophyll meter represents a good indicator for N status, the data collection is both time- and labor-intensive. Moreover, the measurements are carried out in one small point in the leaf only.

As such determining the nitrogen status of agricultural crops by non-destructive optical measurements appears to represent a promising technique for guiding precise fertilization strategies (Reusch, 1997). This technique has the capability of sampling a high number of plants simultaneously (rather than a single leaf point) and of a fast assessment of the spatial variability within a given field. Remote sensing techniques have been used frequently to determine appropriate wavelength and wavelength combinations to characterize chlorophyll content (Osborne et al., 2002), N status (Read et al., 2002) and biomass production of crops (Flowers et al., 2003) as well as grain yield (Schmidhalter et al., 2001). Together these studies have shown that good relationships exist between spectral reflectance signatures and both N status and biomass in different crops.

Using tractor-mounted passive sensing systems such as "Hydro N-sensor" (Lammel et al., 2001) or "GreenSeeker" (NtechIndustries Inc., Ukiah, USA, (http://www.ntechindustries.com/greenseeker-home.html), the measurement of reflected radiation is already being applied to detect N supply differences under field conditions. The "YARA N-sensor" has four optical inputs with a 90° azimuth angle between them and the reflected radiation from the canopy is optically averaged through a four-split light fiber. The reliability of the "YARA N-Sensor" to detect spatial differences in N status and biomass of crops in the field has been tested in field experiments of three-years duration using a modified tractor-based field hyper spectral radiometer with a comparable oligo view optical setup. As judged against validations performed destructively on calibration areas of 25 m² varying in nitrogen supply, the results showed that strong correlation exist between reflectance indices and N uptake from the end of tillering to flowering ($R^2 = 0.90$) (Mistele et al., 2004; Mistele and Schmidhalter, 2006, in prep). As such, the tractor-based passive sensor appears to represent a fast and highly suitable means to measure the nitrogen status and biomass of wheat crops. Furthermore, additional developments using a pulse-modulated active sensor allow for measurements to be recorded independent of the time of day.

Another technique to monitor the nutritional status of plants using non-destructive and proximal remote measurements is based on the evaluation of the fluorescence of plant pigments like chlorophyll. The relationship between the ratio of laser-induced chlorophyll fluorescence intensities at 690 nm and 730 nm (F690/F730) and nitrogen supply in winter wheat was characterized using a newly developed field sensor (Bredemeier and Schmidhalter, 2005). Chlorophyll fluorescence was measured at a distance of approximately 3.3 m from the canopy and the sensed area covered approximately 6-7 m². The fluorescence ratio F690/F730 was found to be inversely correlated with N content and uptake and shoot dry biomass. The latter could be determined by means of biomass index measurements independent of leaf chlorophyll content. These results indicate that nitrogen uptake and biomass can be detected reliably through chlorophyll fluorescence measurements under field conditions. In contrast to point data measurements, the establishment of scanning field fluorescence sensors opens new possibilities for N status and biomass measurements. Moreover, because the signal comes from green plant parts only, it has a very low background and is little affected by soil reflectance. Furthermore, biomass detection is already possible at the seedling stage (Blesse and Schmidhalter, 2006, unpublished).

Map- and plant-based site-specific strategies

The "on-the-go" information about biomass and nitrogen status obtained using the sensing methods just described can be combined with a fertilizing algorithm to control the amount of N fertilizer being applied. Unfortunately, however, nutrient recommendations corresponding to within field site-specific characteristics are rarely available (Robert, 2001). This is true not only for the sensor-based approaches, but also for mapping approaches that largely report results from short-term studies. Universal nitrogen fertilizer application strategies for heterogeneous fields simply do not exist. Furthermore, there is no current consensus as to how lower or higher yield productivity zones should be treated. Increasing nitrogen input to weaker crop stands would enhance yields, but is not particularly environmentally friendly. Alternatively, it has been variously argued that higher yield productivity areas should or should not receive higher nitrogen inputs. The situation becomes even more complicated in trying to generalize the strategies for regions that differ in climate and, even more so, in trying to account for any annual variation in climate, which might also interact differently at different locations.

To remedy this situation, static field trials of a long-term or multi-year character were established to test whether targeted, site-specific nitrogen fertilizer application can enhance nitrogen use efficiency as compared to optimal uniform nitrogen application while still maintaining yields (Ebertseder et al., 2005). Mapping and on-line (sensor) variable rate nitrogen fertilizer application strategies were tested in static field trials for several years and at several locations. In general, high yields were found on field sites representing moderate infield variability. Despite highly contrasting weather conditions between years, similar responses of lower and higher yield zones were observed, and the effects of the different strategies were found to be relatively consistent. The results indicate considerable potential to increase nitrogen use efficiency while simultaneously maintaining yields. The mapping approach, which considers the long-term yield potential, indicated substantial gains for the environment in areas of lower yield productivity and fertile colluvial deposit zones, whereas the sensor approach allowed for nitrogen use efficiency to be optimized in areas of higher yield productivity. These results, derived from a multi-year and multi-location field study, recommend the adoption of variable rate nitrogen fertilizer application. The consistency of the results, even in the light of the highly variable annual weather conditions, further allows the generalization of the information obtained and the gains of site-specific nitrogen fertilization to be estimated. In general, it appears that the advantages of site-specific nitrogen fertilizer application increases the higher the yield differences on a field are and the less favourable the weather conditions are.

CONCLUSIONS

Compared to traditional, destructive techniques, the introduction of much simplified on-site testing procedures has the potential to analyse soil nitrate levels very simply and cheaply. These on-farm procedures thus not only allow more frequent determinations, but they also deliver the result in a much shorter time. In particular, the determination of relevant soil properties such as nitrogen content and plant available water capacity by non-destructive sensor techniques appears to be highly effective and will provide long-term information for optimized management. Assessment of the nitrogen content, biomass and nitrogen uptake of plants by optical measurements is also seen as a promising technique. These latter techniques have the capability of sampling a high number of plants in a short time (rather than just a single leaf point), and allow a fast assessment of the spatial and temporal variability of plant growth. Altogether, a rapid assessment of N status and biomass production of field crops will prove useful to determine N requirements in different parts of the field, thereby improving N use efficiency by maintaining yields and product quality, while reducing the risk of surface and groundwater contamination and increasing economic returns.

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