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Silvia Haneklaus
Ewald Schnug

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An agronomic, ecological and economic assessment of site-specific fertilisation

Silvia Haneklaus and Ewald Schnug[1]

Abstract

Fertile soils are one of the most valuable non-renewable resources on earth and agricultural production must preserve their natural status without interfering with other ecosystems. At the same time agricultural production must feed the world population of tomorrow with high quality food. Site-specific fertilisation promises to meet both demands, but even after more than a decade since precision agriculture technologies have been available their implementation on farms is low, because they do not satisfy economic returns. Other problems are the efficient capturing of geo-coded soil and crop information and the development of tailor-made algorithms for the variable input of different nutrient sources such as mineral, organic and secondary raw material fertilisers. It was the objective of this contribution to give an overview of agronomic, ecological and economic aspects of site-specific fertilisation.

Key words: fertilisation, plant nutrients, local resource management, precision agriculture

Zusammenfassung

Eine agronomische, ökologische und ökonomische Einschätzung variabler Düngung

Fruchtbare Böden zählen zu den wichtigsten nicht erneuerbaren Ressourcen auf der Erde und landwirtschaftliche Produktion muss dem Anspruch gerecht werden, deren natürlichen Zustand zu erhalten ohne dabei andere Ökosysteme zu beeinträchtigen. Landwirtschaftliche Produktion soll aber auch die Weltbevölkerung mit hochwertigen Nahrungsmitteln versorgen. Variable, der Variabilität von Ressourcen im Boden angepasste Düngung ist ein vielversprechendes Konzept, welches beiden Ansprüchen gerecht werden kann. Aber auch mehr als ein Jahrzehnt nach Einführung von Precision Agriculture Technologien erfolgte deren Implementierung auf Praxisbetrieben nur selten aufgrund unbefriedigender ökonomischer Profite. Andere Probleme stellen das Erfassen geo-kodierter Boden- und Bestandesinformationen sowie die Entwicklung lokaler, dem Standort angepassten Algorithmen für die variable Düngung mit mineralischen und organischen Produkten sowie Sekundärrohstoffen dar. Ziel dieses Beitrags war es, einen aktuellen Überblick über agronomische, ökologische und ökonomische Aspekte variabler Düngung zu geben.

Schlüsselworte: Düngung, Nährstoffe, Lokales Ressourcen Management, Precision Agriculture

[1] Institute of Plant Nutrition and Soil Science, Federal Agricultural Research Centre (FAL), Bundesallee 50, D-38116 Braunschweig, Germany

1 Introduction

Agriculture was positively associated with food production and food security less than a century ago. It is nowadays commonly linked to problems such as eutrophication of water bodies, enrichment of pesticides in soils and plants and contamination of foodstuff with xenobiotics. Additionally BSE, foot and mouth disease and cropping of genetically modified plants contributed to a tremendous loss of trust in the quality of food. Alternatives for consumers are products from organic farming which 'inter alias' bans industrial nitrogen fertilisers and pesticides completely and which acknowledges ethical aspects of livestock production. Precision agriculture technologies implemented on conventional farms could be an important step to regain the confidence of consumers through limiting the input of fertilisers and agro-chemicals to the minimum requirements.

Fertilisation is indispensable for crop production independent of the management system. Site-specific fertilisation appeared to be a proper solution for more efficient nutrient management, which would reduce input costs, increase or secure crop productivity and minimise environmental burdens at the same time. But what seemed simple at first sight, proved to be difficult to realize. The major problem is that site-specific fertilisation has very rarely been economic on a full cost calculation. Further, the efficient gathering of geo-referenced soil and crop information, algorithms for their interpretation and, last but not least financial investments for hardware, hampered the acceptance of farmers. So, the bottom line is that after more than ten years of development the worldwide area of agricultural farmland where site-specific fertilisation is regularly applied still does not register statistically. The premise for a solution to this problem is that ways are found to make precision agriculture economically viable.

It was the aim of this contribution to present current approaches on how agronomic demands towards site-specific fertilisation can be satisfied, to discuss ecological impacts, to analyse economic properties for different scenarios and to propose practical opportunities for increasing the profitability of precision agriculture technologies.

2 Meeting the spatial variation of natural resources

Man has probably been aware of the problem of the spatial variability of soil characteristics ever since cropping began but until the end of the second millennium no suitable technique was available to tackle it. It has been the invention of geostatistics by Krige (1951) and Matheron (1971), the access to satellite aided positioning (GPS, Global Positioning System; Bauer, 1994) and the development of affordable fast computers with ample storage capacities which have provided the key technologies for solving this ancient problem in land use. Local Resource Management (LRM) is a concept which addresses the small scale variability of soil and crop features and consequently transforms this knowledge into variable rate applications (Haneklaus and Schnug, 2000).

A uniform fertiliser rate will never match the site-specific nutrient demand resulting in unsatisfying cases of nutrient deficiency and surplus, with these firstly not covering the potential yield, and secondly having strong impacts on ecosystems resulting in an unsustainable use of resources (Haneklaus and Schnug, 2000). Site-specific fertilisation aims to record and predict the spatial variation of the nutrient supply in the fields and finally transcribe it onto variable fertiliser rates. An example for the discrepancy between site-specific phosphorus demand determined on the basis of the spatial variation of the plant available phosphorus content in the soil and the supply by a uniform application rate is demonstrated in Figure 1.

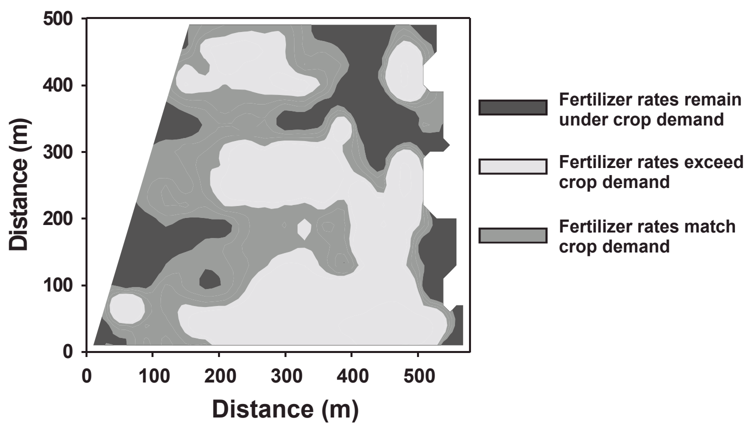

Fig. 1
Discrepancy between phosphorus demand, based on the spatial variation of the plant available phosphorus content in the soil and actual phosphorus supply by a uniform application rate on a field in Lower Saxony (E 9.48191; N 52.54643)

3 Agronomic aspects of site-specific fertilisation

Fertilisation with natural products such as plant residues, lime, gypsum manure, compost, sludge and others for maintaining soil fertility is as old as farming itself. It was the mineral theory of *Liebig* (1803-1873), which revealed that fertilisation is vital in order to produce high yielding crops of prime quality. In total 13 mineral nutrients are essential for higher plants: nitrogen (N), phosphorus (P), sulphur (S), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), chlorine (Cl), boron (B) and molybdenum (Mo).

Strategies for site-specific fertilisation need to take into account target of crop production, available data and type of fertiliser product. A spatial variation of the nutrient demand, which justifies site-specific fertilisation, is an imperative prerequisite.

In developed countries the primary target of site-specific fertilisation is to maintain or increase crop productivity through improved input utilisation, but only if the costs for site-specific fertilisation are lower than the increased profit. The primary target in developing countries where foodstuff is a valuable commodity, is to maximize crop production at a given input as the availability of fertilisers is often restricted and possible expenditures limited. To a limited extent these conditions can be compared to low input systems such as organic farming. Here, rates should follow the strongest response in terms of yield.

Strategies for the variable rate input of fertilisers require information about the spatial variation of the nutrient demand. Such information can be provided in its simplest form by local know-how. Usually, however, soil samples are taken to predict the nutrient demand. As grid soil sampling is far too costly and time-consuming, alternatives such as directed sampling and ground-based sensors may be employed (see 3.1).

Strategies for site-specific fertilisation need to take into account different forms of fertilisers such as single nutrient mineral fertilisers, compound fertilisers, organic fertilisers and secondary raw material fertilisers, because either mono-factorial or multi-factorial rules need to be elaborated. While approaches for the site-specific application of compound fertilisers exist, equivalent systems are still missing for secondary raw material products and organic fertilisers (Haneklaus and Schnug, 1999a). The specific problem of their site-specific application is the fact that they contain different nutrients in varying concentrations, which need to respond to changing soil properties. Strategies for the variable rate application of farmyard manures and secondary raw material fertilisers are most urgently required because of environmental concerns. These nutrient sources may be of higher significance for a successful development of precision agriculture than manufactured fertilisers because of the strong need to control their fate and environmental impacts and because the costs of applying precision agriculture can be covered by the main use of the primary product.

4 Capturing geo-coded soil and crop data

Currently, the following sources of information and methods are used to assess the spatial variation of relevant growth parameters:

Local knowledge. Local knowledge stands for information which is available on a farm, either in form of amateurish maps, field files and any other materialized form of store (Haneklaus and Schnug, 2002). Firstly, it is a valuable source of information to assign management zones (Fleming et al., 2000) and to decide on fertiliser rates. The simplest way of employing local knowledge for site-specific fertilisation would be the manual adjustment of fertiliser rates (Fixen and Reetz, 1995). This procedure is certainly limited to the larger farm size; then PA technologies need to be implemented, but it will remain an efficient source of information and decision making. Another relevant local knowledge for site-specific fertilisation on small farms is that of geomorphology. The assessment of basic terrain information may be used to set up surprisingly efficient strategies for site-specific fertilisation (Haneklaus and Schnug, 2002).

Sampling of soil and plant material. The nutritional status of crops can be quantitatively assessed either by soil or plant analysis. Detailed guidelines for collecting, handling and analysing plant and soil material are given by Reuter et al. (1997) and Collins and Budden (1998). It is important that samples are geo-referenced and taken within an area of not more than 10 m^2. The traditional mixing of 15-30 sample cores per hectare interferes with the variability of soil features and is therefore unsuitable (Haneklaus et al., 1998a).

Soil properties can vary at different scales of spatial resolution depending on the pedogenesis of the landscape and farm management practices. Thus the scale at which geo-referenced soil information can be gathered directly influences the accuracy of the data. The smallest operational unit should be the pedon, which represents the smallest homogenous unit or area in a field in terms of soil factors influencing nutrient dynamics and soil classification features. The size of a pedon depends on the landscape and may be as small as 1-10 m^2 (Schroeder, 1977/78). A finer scale of inspection will most likely cause decoherence so that site-specific fertilisation at this scale would be pointless (Lark, 2001).

Traditional discrete sampling procedures are either grid-based or statistically based at random. Grid distances of 30 to 50 meter may be required in order to accurately determine the spatial variation of crop features and to produce representative agro-resource maps (McBratney and

Pringle, 1997; McBratney and Whelan, 1999; Haneklaus et al., 1997). Geo-referenced grid soil sampling is, however, not operational on farm level as it is not cost-effective (Schnug et al., 1998). Approaches for a reduction of sampling efforts which warrant a high accuracy of estimates are for instance the variance quad-tree (VQT) method (McBratney et al., 1999), the management zone procedure (Shatar and McBratney, 1999), self-surveying (Haneklaus et al., 1998b), directed sampling based on remotely sensed images (Mulla, 1997; Haneklaus et al., 2000; Basso et al., 2001) or equifertiles (Schnug et al., 1994).

The VQT method samples sparsely in uniform areas and more intensely where variation is large. Management zones define areas with similar yield response to different factors which are commonly calculated from yield, topographic and soil data by taking advantage of fuzzy partition (Shatar and McBratney, 1999; Lark, 2001). Comparable to management zones are soil indices and equifertiles, which reflect zones of similar crop productivity or soil fertility. They can be derived inductively, based on the spatial variation of key soil fertility parameters, or deductively, based on different levels of crop productivity (Ortega et al., 1999; Schnug et al., 1994). Multivariate analysis is performed for identifying causal reasons for yield differences and for quantifying yield responses to different factors.

Self-surveying is a method by which basic spatial information of for instance soil texture, organic matter content and geomorphology are gathered using surplus labour on farms and human sensory capabilities (Haneklaus et al., 1998b).

Already existing spatial information of a site is used to guide sampling to representative plots, referred to in the literature as directed, smart or targeted sampling. For a further reduction of sampling points, only those locations are selected for permanent investigations which proved to be consistent over time and which comprise the whole range of variation of soil properties and their temporal fluctuations. This minimum number of control points comprises so-called monitor pedo cells (Panten et al., 2002).

The visual diagnosis of plants allows the identification of symptoms of severe nutrient deficiency while growth-limiting conditions remain hidden. The distinct advantage of plant sampling is its closer relationship to growth processes and wider ranges of at least 100 meter compared to minimum ranges of 50 meter for soil parameters (Haneklaus et al., 1997). The major handicap, however, is that it cannot be performed in advance for a new crop so that the period for sampling, chemical analysis and fertilisation is very short.

Ordinary survey maps. Land surveying authorities provide maps about soil geology, hydrology and soil indices, but this data is not always available in digital form with sufficient resolution. Scales range for example from 1:2,000 – 1:5,000 for soil index maps and 1:5000 – 1:10.000 for elevation and 1:25,000 for soil type. So this data is of limited usefulness for decision-making strategies in site-specific fertilisation.

Remote sensing. The number of suppliers of remote sensing images taken from airborne platforms and space vehicles is expected to increase in future and thus extend the limited availability of this information tool. Moran (2000) summarised the agronomic demands towards remotely sensed images by preference: image delivery within 24 hours; geo-reference with an accuracy of one pixel; information accuracy of the measured crop or soil conditions of 70–75 %; repeat coverage ranging from twice per week to biweekly; spatial resolution of 10–20 m; maps providing quantitative information of measured features; fair product prices. A breakthrough of an instant image delivery could be the development of a digital low cost remote sensing system, which provides ad-hoc geo-referenced images by aero-triangulation using high accuracy GPS receivers (Grenzdoerffer, 2001).

Information on spatially variable soil and plant features that can be gathered from remotely sensed images without ground truth is limited. Management zones (Stewart and McBratney, 2001), water or heat stressed areas in the field can be identified (Davis 1997/1998) and thus used for site-specific fertilisation.

Bare soil images are preferable for the investigation of key soil parameters such as organic matter content, soil texture and topography as vegetation changes the reflectance and emission characteristics of the image. An accompanying ground campaign is necessary because of the superimposition of the reflectance characteristics by soil texture, organic matter, water content and ferric oxides (Barnes et al., 1996).

Pedogenetically homogenous zones are closely associated with spatial differences in geomorphology, soil texture and organic matter content, all of which can be assessed by remote sensing techniques (Barnes et al., 1996). As pedogenesis is considered to be similar in each class, it can be expected that non-visible, chemical soil parameters will show comparable similarities. Classified images can be efficiently used for directed sampling of pedogentically homogenous areas in the field so that relative values for soil texture and organic matter content could be subsequently transformed into quantitative data (Mulla, 1997; Haneklaus et al., 2000b and Basso et al., 2001).

Images taken during the vegetative period have a wide operational area, for instance the determination of the canopy size measured by the Green Area Index (GAI), the chlorophyll content measured by the Normalized Difference Vegetation Index (NDVI), the Leaf Area Index (LAI), above ground mass, crop coverage and prognosis of yield (Taylor et al., 2000; De Koeijer et al., 2000).

Among all nutrients N has the strongest effect on the chlorophyll content of plants and reflectance spectra are used to determine NDVI and red edge, which are set in relation to the chlorophyll content or N status. In this context it needs to be outlined that the causal chain: green colour of plants – chlorophyll content – protein content – total N content – N status of plants was extended by N supply of plants from the soil, ignoring basic knowledge of natural science. The first two assumptions are valid 'ceteris paribus' as there are many more factors affecting the green colour of plants and chlorophyll content than just N, as for instance deficiency of other nutrients such as S, K, Mg, Mn, Zn and Cu, genetic dispositions, pests and diseases, drought, water logging, soil compactions and other physiological disorders. Consequently this means that changes of the spectral signature can only be assumed to be caused by a variation of the N supply in the soil under ceteris paribus conditions. The same criticism applies for ground based optical sensors, which are used for a site-specific N management on the go (Wollring and Reusch, 1999).

The present use of remotely sensed images could be supplemented by the following fields of application: the identification of nutrient disorders which would give preference to consumer demands over the interests of producers who distribute this technique to regulate the N input. A wide field for future research and development in site-specific fertilisation will be dynamic soil fertility maps (Russell, 1996; Parker et al., 1996). The synchronisation of inputs to the demand of the growing crop is an old goal of agricultural practice, but it will gain a new dimension when spatially extended. Dynamic modelling, taking the spatial change in which cells influence each other into account, is of particular interest for rapidly changing growth factors such as soil temperature, soil water regime, plant available N and risk assessment of infection with soil borne fungal diseases. Verhagen and Bouma (1998) used dynamic simulation models to predict nitrate losses over winter reliably so that this procedure might serve as a control tool for farm management practices.

Ground based sensor systems. Ground based, invasive and non-invasive soil sensing systems are used to follow up the spatial variation of soil water, nitrate, organic matter, soil pH, soil electrical conductivity that are described in detail by Viscarra Rossel (2001). At present a plant N sensor (Wollring and Reusch, 1999), an organic matter sensor and different sensors determining the electrical conductivity are commercially available (Viscarra Rossel, 2001). Sensor techniques offer the advantage of covering large areas and providing data at high ground resolution, but they will always need ground truthing in order to verify a sufficiently close relationship between sensory data and soil features before transferring this data into application maps.

On a world scale yield sensors are probably most widely used to determine productivity of combinable crops and the characteristics of the different systems are comprehensively discussed by Murphy et al. (1995) and Griepentrog (1999). Yield maps offer the possibility to calculate the nutrient demand on the basis of nutrient removal of each crop and whole crop rotations and thus contribute to a balanced fertilisation.

Stationary, continuous remote sensing of crops by LASSIE. LASSIE (Low Altitude Stationary Surveillance Instrumental Equipment) is an innovative concept for the continuous recording of real-time images of crop and soil surfaces which are automatically rectified and geo-referenced in a GIS (Schnug et al., 2000). LASSIEs describe stationary digital camera or scanner systems with remote controlled variable, horizontal and vertical positioning on elevated places in the landscape.

An important differential diagnostic criteria for identifying the true cause of visible symptoms of plants are spatial patterns and coincidences with soil characteristics which requires the 'real-time' surveillance of crops. During the vegetation period for instance, the spatial pattern of signatures of flowering oilseed rape or ripening barley reflect dynamic information about the spatial variation of the soil water regime. Additionally, the progression of disease and pest development can be tracked if time sequences of less than three days are available. Changes in crop performance become easily identifiable with LASSIE and can be addressed either directly or indirectly by an accompanying directed ground truth. The results of soil/crop analysis can then be more or less instantly transferred into variable rate management on the fields.

Processing of geo-coded data. GIS software suitable for use on farm level needs to be flexible in such way that geo-referenced data can be filed, interpreted, transformed and processed variably. At present there are three special software packages available for site-specific fertilisation: VESPER is designed to perform geostatistical analysis of geo-referenced data which processes large data sets and takes the local spatial structure into account (Minasny et al., 1999). The software package FuzMe marks management zones for site-specific fertilisation by fuzzy classification: available information on soil characteristics may be used directly for the set-up of the classification or class memberships of soil features may be predicted indirectly employing related parameters (Anon, 2001a). The software package LORIS® consists of several modules which enables the import of point and polygon data, the interpolation of geo-referenced data, the generation of digital agro-resource maps, the flexible use of individual algorithms for creating site-specific operation maps and their export to data carriers (Schroeder et al., 1997).

5 Interpretation of soil and plant data

The most important premise for site-specific fertilisation is information of the spatial variability of relevant growth factors, the evaluation of the yield potential and identification and ranking of growth limiting factors. Growth factors are all parameters influencing crop performance, which include biotic and abiotic factors such as climatic conditions, soil fertility, nutrient status of crops, water supply, pests and diseases.

Common rules for fertiliser application have been proposed for decision making in site-specific fertilisation and were directly transferred into fertiliser rates for lime, P, K and magnesium (Mg) (Dampney et al., 1997; Dawson, 1996; Dawson and Johnston 1997; Fotyma et al., 1997). However, there are two major criticisms of such an approach: firstly, the basic fertiliser response curves were mainly established in the 1940's to 1960's and data bases need to be updated and validated for site-specific fertilisation, respectively (Hergert et al., 1997; Voss, 1997). Secondly, established critical thresholds refer to small homogenous plots (Mallarino and Blackmer, 1992) and are therefore counter-productive with a view to the target, which is to identify variability, to match it with a variable input and thus to improve recommendations (Hergert et al., 1997). Additionally, soils and plants were sampled in the past without reference to spatial auto-correlation, so that the whole system of interpretation still used today for recommendation is based on averages, too (Nowak, 1998) and will therefore best yield average results (Oestergaard, 1997; Simmelsgaard and Djurhuus, 1997). Field experimentation, based on soil and plant data, is considered as one of the pillars for developing recommendation schemes, but in the past it consistently aimed at averaging results by arranging replicates across the variability within a field. This example stresses that site-specific fertilisation will be more successful, if more variability and extremes are addressed in experimentation.

Another problem is the calibration of soil and plant data. *Liebig*'s "Law of the Minimum" in 1855 stated that the exploitation of the genetically fixed yield potential of crops is limited by the variable, which is insufficiently supplied to the greatest extent. This theory neglects interactions between growth factors, but proved to be sufficiently accurate to estimate the single response of the nutrient (Lark, 2001), an assumption the upper boundary line approach is subjected to (Webb, 1972). The input of fertilisers in site-specific fertilisation should follow the response curve and yield potential that can be realized under the constraints of the strongest yield limiting factor which cannot be corrected by input of resources or soil tillage operations as for instance the water holding capacity of soils. Here, the technical tools of precision agriculture offer the opportunity to find new solutions for this problem by establishing critical values for each nutrient and each field conducting on-farm experimentation (Schroeder and Schnug, 1995). Geo-referenced data from on-line yield measurements of one or more years are plotted against soil or plant nutrient concentrations and critical nutrient values are derived using the upper boundary line approach (Webb, 1972). An example for the evaluation of optimum plant available P contents in the soil is given in Figure 2. The principle of the boundary line analysis and the application of the *BO*undary *LI*ne *DE*velopment *S*ystem (*BOLIDES*) in site-specific fertilisation are comprehensively discussed by Schnug et al. (1996). A major advantage of using *BOLIDES* in site-specific fertilisation is the distinctly higher number of replicates than in common field experimentation, which increases the accuracy of the results, obtained.

The P values, based on soil sampling in a 30 meter grid were plotted against the relative grain yield data of oats and barley (Figure 2). Erroneous extremes were excluded before further processing of the data. The boundary line, usually a 4th order polynomial function, lies on the upper edge of the body of the data. This line describes the response to variation in the test parameter where all other factors are, within the constraints of the fields concerned, as close as possible to non-limiting in terms of crop yield. Data points below this line relate to samples where some other factor limited the crop response to the nutrient. The first derivative of the fitted polynomial gives predicted yield response to fertilisation in relation to the nutrient content. The optimum nutrient value corresponds with the zero of the first derivative of the upper boundary line and the sign of the second derivative at this point. For the determination of optimum ranges i.e. the range of nutrient

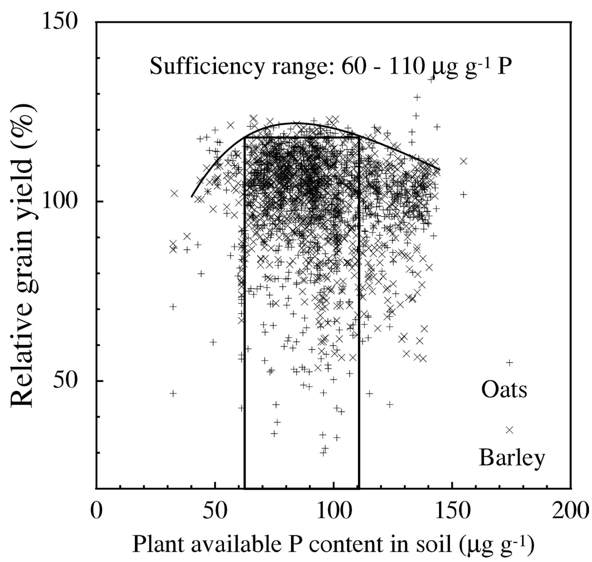

Fig. 2
Evaluation of the optimum range of plant available P contents in the top soil by BOLIDES for a field in Mariensee,
Lower Saxony (9°29.05' E; 52° 33.09' N)

Table 1
Range of variation of nutrient off-take by oats (n= 174) and winter wheat (n=132) determined by 30 meter grid sampling on two fields in Mariensee, Lower Saxony (E 9.48607; N 52.56788)

Nutrient	Grain - Winter Wheat				Straw - Winter Wheat			
(%)	min.	max.	mean	CV (%)	min.	max.	mean	CV (%)
N	1.88	2.17	2.06	3.1	0.41	0.79	0.57	10.4
P	0.31	0.41	0.35	4.4	0.05	0.12	0.08	19.6
K	0.45	0.58	0.50	5.0	1.25	2.17	1.61	11.9
Mg	0.08	0.10	0.09	3.5	0.03	0.01	0.06	14.8
Yield (Mg ha^{-1})	5.9	9.6	8.1	9.5				
	Grain - Oats				Straw - Oats			
N	1.50	2.03	1.82	6.6	0.16	0.61	0.30	26.9
P	0.21	0.39	0.29	13.7	0.11	0.35	0.25	12.4
K	0.35	0.58	0.48	10.5	2.58	4.55	3.68	10.6
Mg	0.05	0.15	0.12	18.0	0.02	0.09	0.05	19.0
Yield (Mg ha^{-1})	4.0	8.6	7.4	8.6				

note: CV - coefficient of variation

concentrations which are sufficient to realize 95 % of the maximum yield, standard, numerical root-finding procedures are used for real polynomials of the fourth degree with constant coefficients. The results reveal that the optimum range is 60 to 100 µg g^{-1} P in order to achieve maximum yields.

6 Transformation of spatial data into algorithms for site-specific fertilisation

The choice of strategies for site-specific fertilisation depends on available spatial information and comprises simple approaches based on local knowledge as well as sophisticated methods employing new technologies for on-farm experimentation.

Fertilisation based on local knowledge. Simple, but nevertheless efficient, general algorithms to regulate N fertilisation may rely for instance on the spatial variation of geomorphological characteristics in elevated landscapes which may be derived from elevation data (Ortega et al., 1999; Nugteren and Robert, 1999; Haneklaus and Schnug, 1999b; Schmidt, 2001) and/or other key parameters influencing the N supply such as soil texture and organic matter content (Haneklaus and Schnug, 2002).

Balanced fertilisation. Balanced fertilisation using yield maps offers another chance of decision making for site-specific fertilisation (Blackmore and Larscheid, 1997; Lark et al., 1997; Larscheid et al., 1997). As biomass production and yield are never fully predictable, nutrient balances calculated for balanced fertilisation will always be prone to a certain degree of uncertainty. The major target of balanced fertilisation in the field is to keep nutrient inputs as close to nutrient outputs as possible, which can only be achieved if soils are treated on their smallest scale of significant variability. The variation of N and other minerals such as P, K and Mg was distinctly higher in the generative material of oats than in winter wheat (Table 1). This may be explained by the fact that oats are a husk grain crop and the share of hulls varies between grains of one panicle (Geisler, 1980).

The variation of macro-nutrients in wheat straw was two to fourfold higher than in grains, but similar in both plant parts in case of oats (Table 1). Therefore, the off-take of plant minerals may be calculated as a multiple of the yield in case of huskless cereals, and if plant residues (straw) remain on the field. In case of cereals with hulls such as barley, oats, rice and millet this might provide unsatisfactory results with view to a balanced fertilization.

Although some authors proposed precision agriculture measures for yield quality, their results reveal that the variation of the N concentration in barley was extremely small (Stafford, 1999; Thylen et. al., 1999).

Fertilisation based on on-farm experimentation. Site-specific fertilisation can be developed genuinely site-specific when precision agriculture tools are employed for on-farm experimentation (see 3.2). After determining optimum ranges for the nutrient supply, in the example given in Figure 2 for plant available P, a strategy for spatially variable rate fertilisation can be derived.

Based on the results of BOLIDES only those zones in the field will be fertilised where the nutrient content is sub-optimum (< 60 µg P g^{-1}). In the example given in Figure 3, the area within the field that was insufficiently supplied with P was only 1%. Variable rate fertilisation based on traditional recommendation schemes would yield a mean expenditure of 20 kg ha^{-1} P and thus promote an unnecessary input of resources.

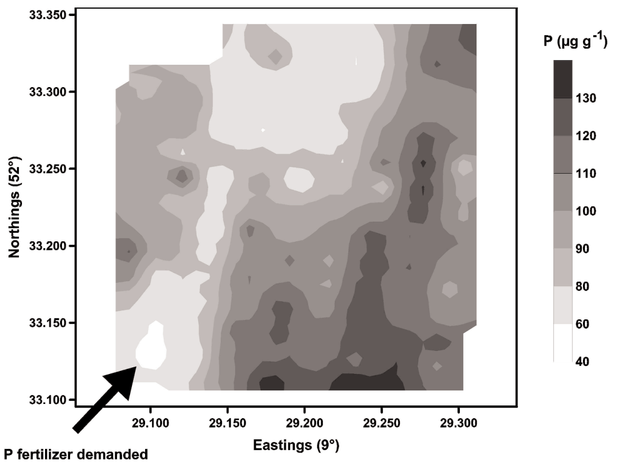

Fig. 3
Digital agro resource map for plant available P contents for a field in Mariensee, Lower Saxony (9°29.05' E; 52° 33.09' N)

7 Ecological aspects of site-specific fertilisation

Site-specific fertilisation aims at meeting the requirements of a sustainable agricultural production through a considerate input of resources, which minimizes negative environmental impacts. Although the ecological prospects of site-specific fertilisation have no impact on the profitability, for the preservation of nature it has beyond doubt every justification. Sparovek and Schnug (2001) claim that precision agriculture technologies should be a directive to be followed by farmers in order to implement Best Management Practice (BMP) globally as they expect proven beneficial, economic and agro-ecological effects only after a certain period of adoption and if the technology is applied on a global scale. An evaluation of the ecological relevance of site-specific fertilisation is given in table 2. Site-specific fertilisation of nitrogen, phosphorus and lime has supposedly the strongest environmental impact. In the case of nitrogen particularly, non-point losses may be reduced by site-specific fertilisation. Until now only sparse information on agro-ecological impacts of site-specific fertilisation is available and therefore effects are mostly speculative. The studies of Whitley et al. (2001) for instance proved that N fluxes in the surface soil were higher and N uptake efficiency was increased after variable rate N fertilisation to potatoes in an elevated landscape.

With phosphorus, an effective reduction of losses by soil erosion of light particles can be expected after site-specific soil tillage operations. Facing limited natural resources of phosphate, which are estimated to satisfy agricultural demands for only another 100 years (Anon, 1996), site-specific fertilisation of phosphorus should be paid attention to straight away.

Generally micro-nutrient disorders are very rarely a problem of insufficient reserves in the soil, but most likely caused by restricted mobilisation. This is particularly a problem on heavy soils which require for the flocculation of soil aggregates a high calcium saturation of clay minerals (Roth and Pavan, 1991) and which is usually warranted by liming. But too high pH values cause an immobilisation of micro-nutrients (Santano Arias and Espejo Serrano, 1997). Under these conditions foliar application of fertilisers is the only possibility to satisfy the nutrient demand of the crop; on a long-term basis site-specific lime applications and possibly substitution of lime by other calcium sources such as gypsum should follow to optimise crop production.

Table 2
Regionalisation of essential plant nutrients and ecological significance of a site-specific nutrient management

Nutrient	Regionalisation	Nutrient	Ecological significance	Key parameters for assessing spatial variation
N		N		geomorphology; organic matter; management zones; equifertiles; soil texture
P		P		management zones; equifertiles
S		Lime		soil pH; soil texture
K		Ca		soil pH
Ca		S		geomorphology; soil texture
Lime		Cu		organic matter
Mg		Zn		soil pH; organic matter
Cu		B		geomorphology; soil texture
Mo				
Mn		Mg		soil pH
Zn		Mo		soil pH
B		K		clay; soil texture
Fe		Mn		soil pH; organic matter; redox potential
		Fe		soil pH; organic matter; redox potential
Cl		Cl		geomorphology

For the assessment of the spatial variation of the supply with nutrients which are ecologically relevant either variables such as geomorphology, organic matter and soil pH can be determined directly, or rates are adjusted on the basis of equifertiles and management zones. Geomorphology is an important variable for mobile elements such as nitrogen and sulphur as their supply can be estimated on the basis of nutrient fluxes in the landscape.

The steadily increasing number and quantity of industrial wastes is intensifying the social pressure on agriculture to dispose of them. Sustainable agriculture should use any resource in such a way that does not compromise the way in which the present and future human needs for food or other agricultural goods are satisfied, and ensures that the quality of the environment and natural resources remains preserved. Practically this implies that the concept of zero accumulation of environmentally relevant elements needs to be applied when such products are used to satisfy the nutrient demand in site-specific fertilisation, which means that the input of environmentally relevant elements equals their losses by plant off-take and leaching.

8 Economic aspects of site-specific fertilisation

Though precision agriculture technologies have been investigated and applied in research for more than ten years, a real breakthrough on the farm level is still out of sight. The implementation of precision agriculture tools on production fields systems makes at best slow progress, because the return of investment is far too low (Schmerler and Basten, 1999; Bullock, 1999; Swinten et al., 2001; Sparovek and Schnug, 2001; Kilian et al., 2001). Promising in terms of increased profit at present is site-specific lime application on fields with a high spatial variation in potential soil acidity and soil texture, where prevailing zones show too high pH values (Parkhomenko et al., 2001).

The major problem of intensive farming systems with a view to the application of site-specific fertilisation is that the input of fertilisers decreased generally and the price level is often low. This means that any higher input of resources needs to pay off in terms of yield and any further reduction needs to warrant crop productivity resulting in a small scale for varying the input. Considering the costs for implementing the technology and assessing spatial information it becomes clear why positive economic benefits are small and scarce. This might even end up in accepting the 'null hypothesis' of McBratney and Whelan (1999), in which the uniform management of fields is most profitable.

The profitability of site-specific fertilisation increases clearly, when fertiliser prices are constantly high, as was the case for P in the former GDR (Witter, 1987) or as it is in countries with a high price level for fertilisers like, for instance, Brazil (Roloff and Focht, 2002). But the situation is problematic in the case of ammonia based N fertilisers where price depends mostly (90%) on the costs for gas (TFI, 2002; IFA, 2002). Here, the rapid fluctuations make investments in new technologies on the farm difficult, particularly if the returns are marginal. An economic advantage can be expected, if contractors provide technologies and services (Luetticken et al., 1997).

9 Perspectives for precision agriculture

Site-specific fertilisation instead of uniform application rates promises the maintenance of crop productivity whilst reducing the input of resources and is an important step towards a harmonisation of agricultural and ecological demands. Its use, however, depends on the profitability of the concept. Priority needs therefore to be given to all measures, which contribute to cover the costs for implementing precision agriculture technologies. This could, for instance, be gained by an alliance between farmers and third parties: insurance companies could make use of spatial yield information to agree a floating system of repayments, on, in case of damage, e.g. by hail; machinery manufacturers might equip tractors and combines with monitoring systems which indicate failures in time so that spare parts and service is available straight away; and contractors may benefit from PA technologies through optimising field traffic and working hours. In this context Ward and Holden (1998) showed that PA technologies significantly improved the efficiency of the machinery in peat production.

Intensive livestock farming is a major contributor to environmental pollution and a political directive limiting herd sizes could efficiently solve this problem. The challenge of site-specific fertilisation for tomorrows agriculture, which is going to be more circumspect with view to the fate of nutrient surpluses, and acting to prevent them, will certainly insist on an ecologically tolerable spatial distribution of farmyard manures, but also the function as a control measure. The costs of precision agriculture from control measures will be much easier to cover than those from site-specific fertilisation or enhanced crop performance.

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