Precision Crop Protection - the Challenge and Use of Heterogeneity

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Editors

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Springer

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Preface

A broad spectrum of weeds, animal pests and pathogens – collectively referred to here as pests – are known to cause considerable quantitative and qualitative losses in crop production worldwide. These yield-limiting biotic stress factors have to be appropriately managed in order to reduce their negative impact on the production of food, feed, fiber and fuel. The world's population is expected to expand to 9.1 billion by 2050. This growth in human population will require an increase in food production of up to 70% over present day production levels. A shift in agricultural production towards the use of biomass for energy and other types of renewable resources will dramatically increase the demand for plant based products. In order to meet this demand, crops have to be protected from pests in an effective, efficient and environmental friendly way. Management in most cases can be accomplished by a combination of mechanical, biological and/or chemical tools and other supportive technologies in integrated control programs.

Pests as well as abiotic stress conditions commonly are heterogeneous in time and space in a production field. In the past heterogeneities in soil, water and nutrient distribution affecting crop growth have been managed by dividing the agricultural area into small units with less heterogeneity. In modern large-scale farming, heterogeneity complicates targeted application of agricultural inputs such as pesticides and fertilizers. Heterogeneity often is ignored, because of the lack of appropriate technology to deal with it. Control options, such as the application of pesticides are applied uniformly across the field and can result in over- and under-dosing which in both cases is inefficient and uneconomical and can be an environmental burden.

Precision farming, including site-specific management (SSM), describes an agricultural management system using computerized information technologies (IT) – global navigation satellite systems (GNSS), geographic information systems, remote sensing devices, data management systems and telecommunications – for optimal use of nutrients, water, seed, pesticides and energy in heterogeneous field situations. Precision farming relies upon (I) intensive sensing of environmental conditions in the crop, (II) extensive data handling and processing, (III) use of decision support systems (DSS), and (IV) control of farm machinery (actuators) in the field (Fig. 1). Information from soil and/or crop maps or online information from remote sensing on soil status and crop growth is typically used in combination with GNSS

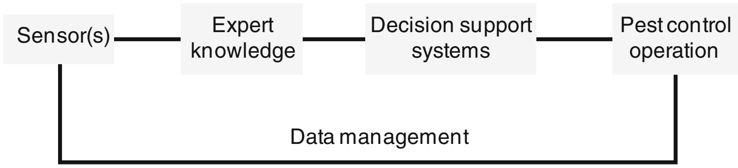

Fig. 1 Information technologies and data management for precision crop protection

data in order to optimize application and/or the timing of inputs to match the natural heterogeneity in the field.

Awareness of potential negative side-effects of agricultural practices on the environment has been a major driver of the concept of precision crop protection. Site-specific management means doing the right thing, at the right place and at the right time. Spatial and temporal variability of pests in the field is no longer ignored, but used in a systematic approach that minimizes the amount of pesticide applied by stipulating demand-oriented application without a reduction in the efficiency of crop protection and crop productivity.

Information technology is used to tailor crop protection activities to achieve effective control when and where needed by monitoring the crop during the crop cycle using DSS for site-specific decision making and by controlling the actuators during application of control options. Decision support systems are based on algorithms that simulate crop growth, the epidemic spread of pests in space and time and the final yield loss of the crop to be prevented by suitable control measures. Information from various spatial scales – plant, canopy or growing region – may be used to assess the variability of crop status.

Site-specific demand has to be assessed by detailed recording of spatial distribution and development of the pest groups and the evaluation of their potential economic impact on crop yield. This situation-specific, threshold-oriented and environmental friendly form of pest management requires large-scale and georeferenced monitoring of pests in the crop for precise timing and application of control measures. In addition to high capacities in data processing and exact regulation of actuators, innovative sensors are crucial for SSM as they generate the input information needed for decision making.

Sensing of heterogeneities in the field is the prerequisite for timely and spatially adjusted management. Recent developments in sensor technologies have led to a broadening of their capacity to detect pests and thereby improve application in crop protection practice. These sensors can be space-borne (satellite), air-borne (airplane, unmanned aerial vehicle) or ground-based (handheld, vehicle-mounted) and provide spatial information that has added value to conventional methods of soil and crop monitoring. Sensing and then reacting is linked by a powerful system of data management that includes DSS. The detection of within-field differences in crop status or growth conditions would enable a farmer to streamline input factors thereby optimizing his profit margin, while simultaneously improving the overall stability of the agro-ecosystem.

The pest groups that have to be monitored for precision crop protection differ greatly in size, patterns of incidence and epidemic spread within and between growth periods of the crops. Heterogeneity of weeds is often obvious and applications for site-specific control of weeds by targeted mechanical or chemical control have reached an advanced stage (Table 1). In contrast, the detection, identification and quantification of pests groups which are highly variable in space and time, is still in developmental stages.

A recent example for the use of information technologies for Integrated Pest Management on a national scale is the Pest Information Platform for Extension and Education (PIPE, http://sbr.ipmpipe.org/). This is a nationwide warning system to help USA soybean growers protect their crop against *Phakopsora pachyrhizi*, an invasive fungus causing Asian soybean rust (ASR). A website provides information for the detection and management of ASR as well as maps of confirmed ASR incidence across the USA and is an effective online warning system. The information is used by farmers and scientists that monitor and analyze disease spread in relation to environmental conditions in order to predict disease spread and to decide whether fungicide use is necessary or not. PIPE has created a high level of collaboration among governmental agencies, growers, agribusinesses, and scientists and has proven the suitability of IT in crop protection.

The assessment and management of arthropod pest and disease heterogeneity in crops is still a major challenge. Basic information is still required on: ground truth patterns of major air-borne diseases; epidemiology; spread and impact of latent infections; optimum time of spraying; (spectral) signatures of infected crops for the identification of diseases and arthropod pests; data handling for on-the-go applications. The influence of SSM on the epidemiology of the pest or multiples thereof over growing seasons also is required in order to evaluate the sustainability of site-specific control concepts.

Table 1 Current status of the control of various pest groups using precision crop protection technologies

Trait	Weeds	Nematodes	Insects	Pathogens
Size of organism [mm]	10–1,000	0.1–1	0.1–00	0.0001–1
Cycles per season	1	1–5	1–8 (?)	1–9 (?)
Mobility	Very low	Low	Low to high	High
Field heterogeneity	XX(X)	XX (X)	X(X)	X(-)
Detection	Individuals XX	Disease sympt. X(X)	Individuals, sympt. (X)	Disease sympt. (X)
Identification	XX	–	?	?
Quantification	XX	(X)	(X)	(X)
Prognosis/DSS	X(X)	X (X)		(X)
Data management	Off/on-line	Off-line		
Application technique	XX(X)	X	(X)	(?)

XX advanced stage; X first steps/moderate knowledge; ? not known/not feasible; - knowledge low

Future technical innovations, such as networked wireless sensors, meteorological sensors as well as nano-sensors for recording plant status, scattered over fields are expected to provide the farmer with site-specific data on crop and soil conditions. The detection, identification and quantification of infections on plants by high powered optical sensors should result in an objective and automated assessment of pests in the field. Automatic systems that use sensors and artificial intelligence to predict the needs of crops and respond accordingly in order to control the primary incidence of pests without human intervention (ambient intelligence) may be available in the foreseeable future.

Since 2001, a Research Training Group at the University of Bonn, Germany, entitled 'Use of Information Technologies for Precision Crop Protection' and funded by the German Research Foundation (DFG) is investigating the potential and limitations of SSM of weeds and pathogens. The Research Training Group organized a workshop on Precision Crop Protection as a post-conference meeting of the 2005 European Conference on Precision Agriculture in Uppsala, Sweden and in 2007 a scientific conference in Bonn, Germany. The number of active participants reflected both an increase in scientific interest in precision crop protection, as well as progress in developing appropriate strategies and tools for solving problems and developing suitable systems for field application.

This book reviews the state-of-the-art of research on precision crop protection and recent developments in the application of site-specific technologies for the practical management of weeds, arthropod pests, pathogens and nematodes with examples from the field. The chapters discuss a wide range of modern technologies that includes information on: (I) the biology and epidemiology of pests, (II) new sensor technologies, (III) application of sensors on different scales, (IV) sensor detection of pests in growing crops, (V) data management, (VI) impact of pest heterogeneity and (VII) precise mechanical and chemical pest control.

Examples for the use of precise application technologies are given for the management of weeds, arthropod pests and diseases which will enable growers to vary application timing, dosage and optimize pesticide mixtures or intensity of mechanical weeding according to the spatial and temporal variability of those pests. Sprayers and mechanical weeders controlled via computer terminals coupled to differential GNSS are described. In addition, decision algorithms developed for automatic regulation of application technology are presented that define the most effective and selective control measure at each site-specific location in a field.

The chapters in this book demonstrate that technologies for precision crop protection had an impact on IPM in the past and will continue to contribute significantly to improved plant health management. The technologies presented here will result in targeted pest control, lower pesticide residues, reduced environmental impact and lead to higher yields at a lower cost to the growers.

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Part I
Spatial and Temporal Heterogeneity of Crops, Pests, Diseases and Weeds – Causes and Implications

Chapter 1
Soil Heterogeneity and Crop Growth

Viacheslav I. Adamchuk, Richard B. Ferguson, and Gary W. Hergert

Abstract Producers around the world are considering the use of precision agriculture technologies. One of the key factors encouraging this development is the spatially varying performance of agricultural crops. In many instances, yield variability can be associated with differences in soil attributes across agricultural fields. Understanding and managing spatial variability in soils has become one of the main strategies to optimize crop production, based on local needs for fertilizer, lime, water and/or other crop production inputs. This chapter presents some basic concepts related to the formation of soil heterogeneity and discusses several ways agriculturists can account for spatial variability in soils through differentiated cultural practices and management.

1 Sources and Scales of Soil Heterogeneity

Since the last decade of the twentieth century, agriculturalists have become increasingly interested in using information-based agriculture for agronomically and/or economically optimized crop production systems (Sonka et al. 1997). One of the most obvious strategies is site-specific management, or, more generally, precision agriculture (Pierce and Nowak 1999), earlier termed farming by soil (Robert 1993). To see the reasons soil variability is linked with inconsistent crop performance, it is important to understand what causes even the best-managed agricultural fields to provide significantly different growing environments from one location to another (Webster 2000, McBratney et al. 2003).

The initial factors influencing variability in soils are related to five soil-forming characteristics: parent material, climate, topography, organisms (including vegetation) and time (Jenny 1941). These factors result in soils which are unique and varied on several scales – global, regional, among and within fields, down to the soil

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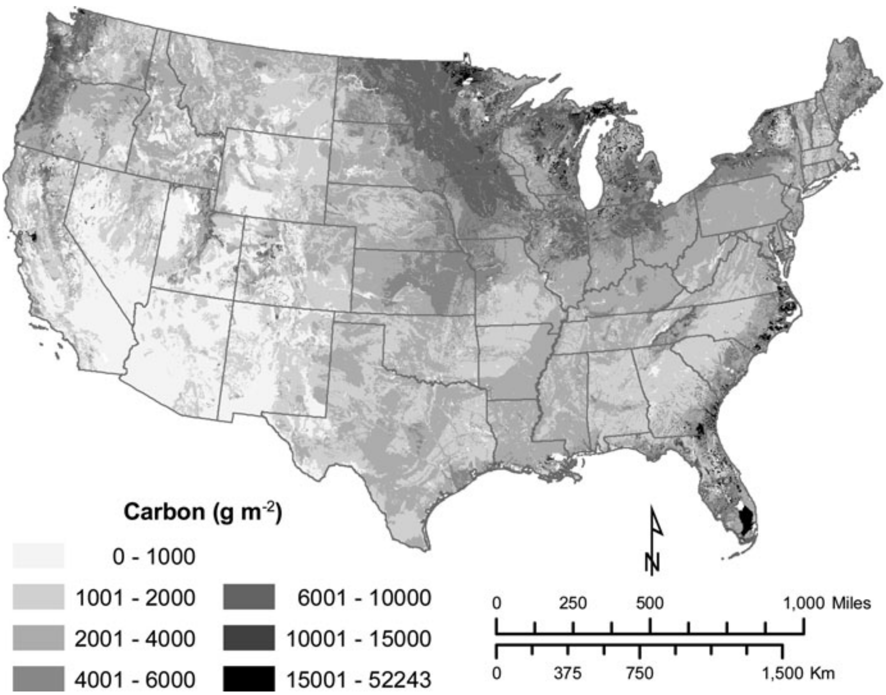

Fig. 1.1 Organic carbon in the top 1 m of soil throughout the contiguous United States provides an example of soil heterogeneity on a regional scale.
Source: United State Department of Agriculture Natural Resources Conservation Service, State Soil Geographic Database (STATSGO)

aggregates. These naturally occurring sources of variability dominate as primary influences on soil heterogeneity on global and regional scales. Figure 1.1 provides a good example, illustrating soil organic carbon in the top 1 m of soil across the continental United States. Soil organic carbon tends to be higher in regions with cool and/or wet climates, as well as in areas dominated by forest or prairie vegetation. It is lower in hot, dry regions.

On the field and sub-field scales, naturally occurring variability can remain quite significant, but historic management enters in as another important factor influencing variability. Figure 1.2 is an example of both natural and management factors affecting soil properties – in this case, soil color, which relates to soil organic matter and productivity in general. Located near the Platte River in central Nebraska, the field contains alluvial soils, with patterns associated with repeated flooding and deposition of sand and silt. The background aerial image obtained in the mid-1950s can be used to identify field areas with relatively light and dark soils, originating from both natural processes as well as management. Some patterns of darker soil are irregular or curved, resulting from silt deposition. Other patterns of darker soil are regular and linear, resulting from historic use of the land. In this case, the lighter-colored block in the eastern part of the image is an old field tilled and leveled

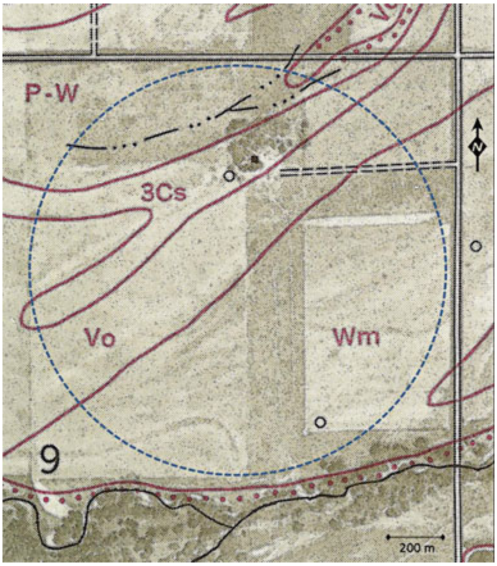

Fig. 1.2 Aerial image and soil series boundaries for a field in Hall County, Nebraska, USA. Vo = Volin silt loam; Wm = Wann loam; 3Cs = Cass fine sandy loam, deep; P-W = Platte-Wann complex.
Source: Hall County Nebraska Soil Survey, United States Dept. of Agriculture, January 1962. The *dashed line* represents the current field boundary

for furrow irrigation in the mid-1950s or earlier. The darker soil region surrounding this block was not tilled until the mid-1980s. Consequently, the portion of the field with a longer tillage history contains about half the soil organic matter of the more recently tilled soil. This image illustrates field boundaries which may be evident in patterns of crop growth many years later, when the entire field within the dashed outline is managed as one unit.

Applying soil amendments such as fertilizer and lime can also impact the heterogeneity of soil properties. The effects can be short-lived or persistent. Figure 1.3

Fig. 1.3 Aerial image of a furrow-irrigated maize field at V12 growth stage, Clay County, Nebraska, USA

illustrates both natural and management-induced patterns of crop nitrogen status. As nitrogen in soil is very dynamic, heterogeneity in soil's N supply is dynamic as well. Light areas within this field are deficient in crop nitrogen, while darker areas have an adequate supply of nitrogen to meet crop requirements at this growth stage. Irregular, curved patterns of N deficiency are associated with lower landscape positions in the field where water accumulated and caused denitrification. The regular, linear stripes across the field are the result of uneven nitrogen fertilizer application. Darker stripes received more fertilizer; lighter stripes received less. These regular patterns of uneven fertilizer application are more pronounced in lower/wetter areas of the field, where denitrification was greater.

Figure 1.4 is another example of management-influenced soil heterogeneity. Currently, this field is managed as a 60 ha center-pivot irrigated field. This field was subdivided into 11 smaller fields. At one time, a farmstead was located in the southwest corner of the field. Livestock manure was spread on the field nearest the farmstead. As a result, substantial immobile nutrients accumulated in places where the manure application rate exceeded the rate of crop nutrient removal. Colored dots in Fig. 1.4 represent soil phosphorus (P) measurements, with soil P concentrations in the southwest corner exceeding 100 mg kg^{-1}. Patterns of soil P concentration throughout the rest of the field are to some degree associated with soil series patterns. The Blendon soil series (Bed and BedA) are lower landscape position soils than the Hord (Hd) soil series. The area of higher soil P associated with Blendon soils periodically has lower crop yields due to saturated soil following heavy rains and loss of plant population. The crop removes less phosphorus due to this saturation in some years, which leads to the gradual accumulation of fertilizer P.

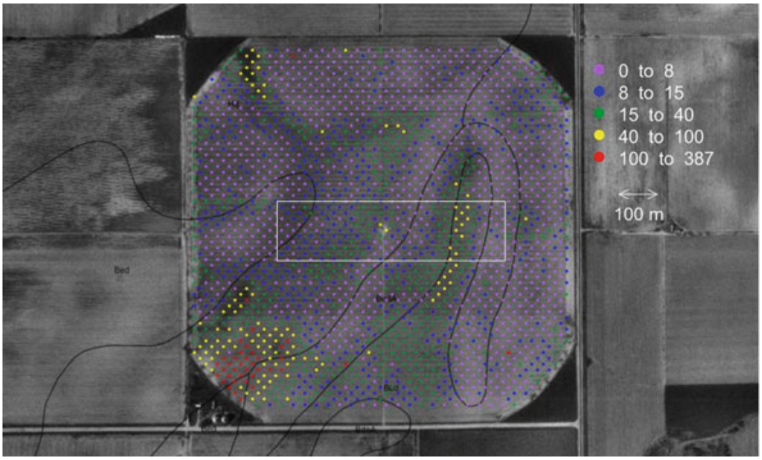

Fig. 1.4 Aerial image and soil series boundaries for a center-pivot irrigated field, Buffalo County, Nebraska, USA. Soil sample locations with Bray-1 P (mg kg^{-1}) concentrations in the upper 20 cm are superimposed

Figure 1.1 illustrates heterogeneity on the national scale; however, for purposes of crop management, variability on the field and sub-field scale are of greatest interest. Agriculturalists must sample thoroughly to accurately determine variability in the soil properties of interest. When designing a sampling procedure for the field, any known factors which may influence patterns of soil properties (e.g., historic manure applications or the former presence of a farmstead) should be considered. Figure 1.5 is a detailed section from the middle of the field illustrated in Fig. 1.4, showing trends in soil P concentration with samples collected every 24 m. Trends over distances of 100 m and greater are consistent with changes in soil series and topography; variability at distances of 50 m or less are more likely related to management.

Figure 1.6 illustrates soil P heterogeneity in both horizontal and vertical dimensions. Created using a transect sampling of a ridge-tilled row in 5 cm increments (horizontally and vertically), this graph illustrates the formation of a band of high soil P concentration. With ridge-till systems, the row location is maintained from year to year, often with repeated application of starter fertilizer at planting. Soil

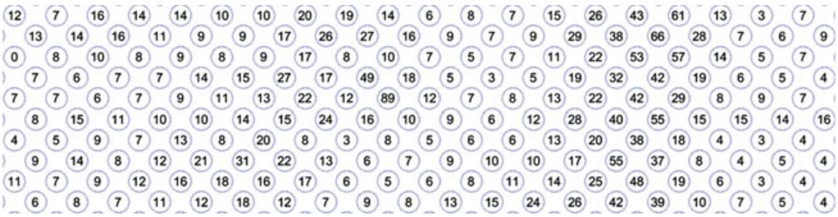

Fig. 1.5 Transect subsection from Fig. 1.4, illustrating variability in soil Bray-1 P (mg/kg) concentration every 24 m

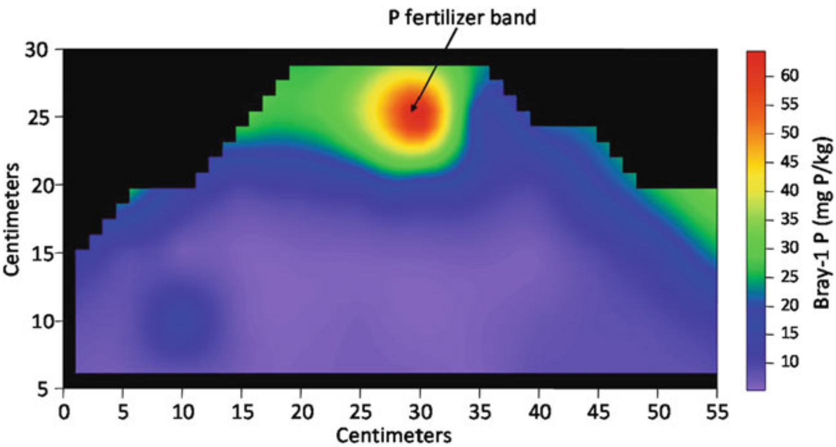

Fig. 1.6 Cross-section across a ridge-tilled row, of Bray-1 P concentration (Clay County, Nebraska, USA)

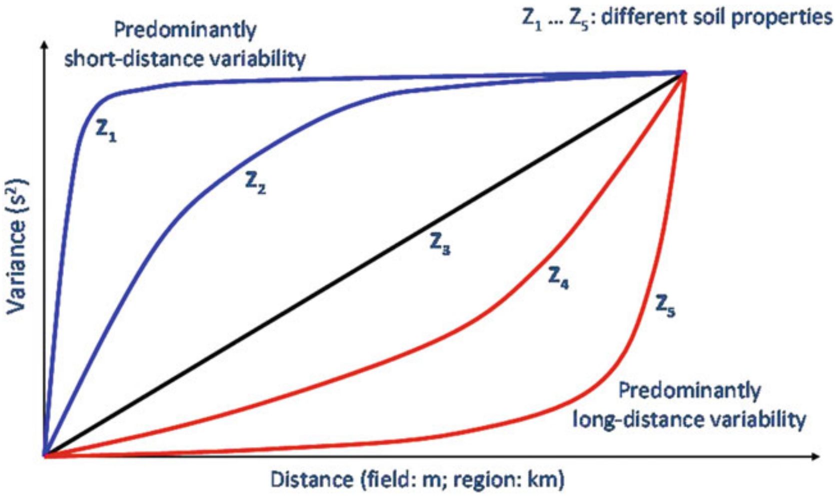

Fig. 1.7 Different potential relationships between sample distance and variance

P concentration varies significantly in both horizontal and vertical dimensions, but in a predictable pattern, given the history of ridge tillage and starter fertilizer use. Knowing this, the agriculturalist can derive a sampling technique which accurately represents the availability of soil P to the crop.

The spatial scale of variability for a given soil property of interest can differ with the property (Fig. 1.7). Some properties, such as soil nitrate, are highly variable over short distances (mm to m). Other properties, such as soil carbon, vary primarily over distances of m to km. Table 1.1 lists ranges of semivariogram models (measures of soil spatial structure) and coefficients of variation for several influential soil attributes (Mulla and McBratney 2000).

Soil properties can vary over time as well as space. Also, some properties are highly dynamic, changing rapidly with time, while other properties are relatively static, varying little from year to year. In assessing spatial variability, temporal variability can sometimes prove to be an important factor. Dynamic properties may change at different temporal scales as well. For example, at shallow depths, soil temperature follows one pattern diurnally and a different pattern seasonally. As depth increases, these patterns are dampened until at some depth temperature is almost constant. Other examples of highly dynamic properties are: soil moisture, microbial activity, water soluble salts, nutrient concentration in soil solution, and soil redox potential. Examples of relative static properties include: soil depth, texture, color, cation exchange capacity, and bulk density.

2 Methods of Assessment

To properly account for existing soil heterogeneity, agriculturalists must assess and interpret measures of mechanical, physical, chemical, biological and other phenomena related to various processes occurring within the root zone. Traditionally this