The normalized difference vegetation index (NDVI) GreenSeeker™ handheld sensor:

Toward the integrated evaluation of crop management

Part A: Concepts and case studies

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Introduction

A. Plant reflectance and normalized difference vegetation index (NDVI)

Reflectance is the ratio of energy that is reflected from an object to the energy incident on the object. Spectral reflectance of a crop differs considerably in the near infrared region (λ = 700-1300 nm) and in the visible red range (λ = 550-700 nm) of the electromagnetic spectrum (Kumar and Silva, 1973; Figure 1). Plants generally have low reflectance in the blue and red portion of the spectrum because of chlorophyll absorption, with a slightly higher reflectance in the green, so plants appear green to our eyes. Near infrared radiant energy is strongly reflected from the plant surface and the amount of this reflectance is determined by the properties of the leaf tissues: their cellular structure and the air-cell wall-protoplasm-chloroplast interfaces (Kumar and Silva, 1973). These anatomical characteristics are affected by environmental factors such as soil moisture, nutrient status, soil salinity, and leaf stage (Ma et al., 2001). The contrast between vegetation and soil is at a maximum in the red and near infrared region. Therefore, spectral reflectance data can be used to compute a variety of vegetative indices that are well-correlated with agronomic and biophysical plant parameters related to photosynthetic activity and plant productivity (Ma et al., 2001; Adamsen et al., 1999). The NDVI is successful in predicting photosynthetic activity, because this vegetation index includes both near infrared and red light. Plant photosynthetic activity is determined by chlorophyll content and activity. The relationship between leaf N and leaf chlorophyll has been demonstrated for maize (Piekielek and Fox, 1992; Chapman and Barreto, 1997) and wheat (Evans, 1989).

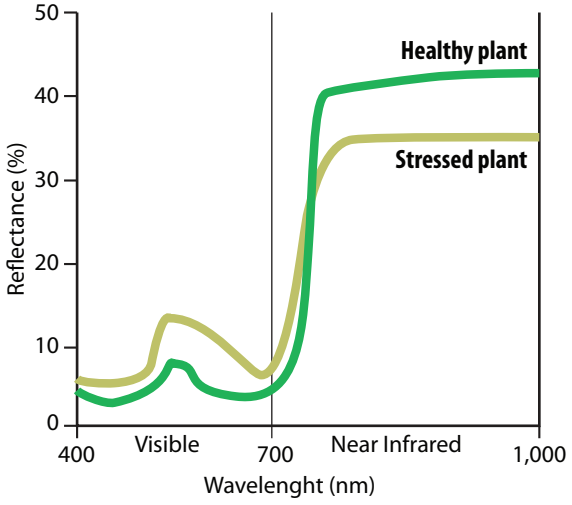

Figure 1. Typical reflectance spectrum of a healthy and a stressed plant.

The NDVI is calculated from reflectance measurements in the red and near infrared (NIR) portion of the spectrum:

$$NDVI = \frac{R_{NIR} - R_{Red}}{R_{NIR} - R_{Red}}$$

where R_{NIR} is the reflectance of NIR radiation and R_{Red} is the reflectance of visible red radiation.

The NDVI has been correlated to many variables such as crop nutrient deficiency, final yield in small grains, and long-term water stress. However, rather than exclusively reflecting the effect of one parameter, NDVI has to be considered as a measurement of amalgamated plant growth that reflects various plant growth factors. The physical characteristics detected by the index are likely related to some measure of canopy density (i.e. leaf area or percent cover) or total biomass. Therefore, the underlying factor for variability in a typical vegetation index cannot be blindly linked to a management input without some knowledge of the primary factor that limits growth. For example, in a field where N is the limiting factor to growth, the NDVI may show a strong correlation with the N availability in the soil; however, in another field, where water is the limiting factor, the NDVI may be just as strongly correlated with plant-available soil moisture.

There are different vegetation indices; however, those that rely on NIR and red reflectance as their principal inputs will typically yield the same information as the NDVI. One of the reasons for the popularity of the NDVI is that many sensors (from handheld to satellite) provide measurements in the NIR and red portion of the spectrum. NIR is also used in color infrared photographs. Most, if not all, of the new commercial satellites will have red and NIR bands, so the availability of these data will increase.

Further reading

Araus, J.L., J. Casadesus, J. Bort. 2001. Recent tools for the screening of physiological traits determining yield. In: M.P. Reynolds, J.I. Ortiz-Monasterio, A. McNab (eds.), Application of physiology in wheat breeding. Mexico, D.F.: CIMMYT. Pp. 59-77.

B. NDVI and remote sensing: A small review

Satellite-based NDVI are influenced by a number of non-vegetation factors: atmospheric conditions (e.g. clouds and atmospheric path-specific variables, aerosols, water vapor), satellite geometry and calibration (view and solar angles), as well as soil backgrounds and crop canopy (Holben 1986; Soufflet et al. 1991; Justice et al. 1991). The angle of incidence of solar radiation also has a strong effect on vegetation indexes (Pinter 1993). However, these complications can be avoided by using the GreenSeeker™ handheld optical sensor unit to measure NDVI. Designed at Oklahoma State University, and commercialized by Ntech Industries, the GreenSeeker™ cancels out the disturbing effects of atmospheric interference and satellite geometry since it is held closely above the crops. Moreover, the handheld sensor contains its own light source, allowing measurements to be taken day or night without interference of sunlight and sun stand. Lack of effect of climate as well as sun angle was confirmed by an independent study as reported on the Oklahoma State University website (http://nue.okstate.edu). This is a great advantage compared to the satellite-based measurements. The high resolution obtained with this handheld sensor makes proper measurement possible at the plot level in contrast with the low resolution typical for air or space remote sensing material. The handheld sensor is non-destructive and the sensor samples at a very high rate (approximately 1,000 measurements per second) and can easily and time-efficiently measure a whole plot representative area. There is, however, still important scope for research on the comparison of the NDVI handheld sensor with satellite imagery, especially when scaling out of results and models becomes important.

C. A case study in the Mexican highlands

Description of the experimental area and design

The case studies that are used as examples here were all done in a long-term tillage trial located at El Batán in the semiarid, subtropical highlands of central Mexico (2,240 m a.s.l.; 19.318N, 98.508W). The mean annual temperature was 14°C (1990-2001) and the average annual rainfall was 600 mm per year, with approximately 520 mm falling between May and October. Short, intense rain showers followed by dry spells typify the summer rainy season and the total yearly potential evapotranspiration of 1,900 mm exceeds rainfall throughout the year. The El Batán experiment station has an average growing period of 152 days. The soil is classified as a fine, mixed, thermic Cumulic Haplustoll (Soil Survey Staff, 2003) or as a Cumulic Phaeozem (International Union of Soil Sciences (IUSS) working group World Reference Base (WRB), 2006). El Batán's climate is representative of many highland areas in the regions of West Asia and North Africa, as well as the Southern Cone and Andean highlands of South America, the central highlands of Ethiopia, the Mediterranean coastal plains of Turkey, and the highlands of central Mexico (van Ginkel et al., 2002).

The experiment was started in 1991 as described in Fischer et al. (2002). Individual plots are 7.5 m by 22 m. Standard practices include the use of recommended crop cultivars, with maize planted at 60,000 plants per hectare in 75 cm rows and wheat planted in 20 cm rows at 100 kg of seed per hectare. Both crops are fertilized using urea at 120 kg N per hectare. Weed control is done using appropriate, available herbicides as needed and no disease or insect pest controls are utilized, except for seed treatments applied by commercial seed sources. Planting of both maize and wheat depends on the onset of summer rains but is usually done between June 1 and 15.

The experimental design consists of a randomized complete block with two replications. There are 32 treatments. The core set of 16 management practices was based on variation of (1) crop rotation (monocropping vs. a maize/wheat rotation); (2) tillage (conventional vs. zero tillage); (3) residue management (retention vs. removal). A second set of treatments was established in 1996 and includes treatments with partial residue retention and planting on permanent raised beds. In the case studies used, only the core set of 16 practices will be considered that were all installed in 1990 and kept since. Table 1 summarizes the considered practices.

Table 1. Treatments at the CIMMYT long-term tillage trial at El Batán, Mexico.

Tillage	Zero tillage		Conventional tillage	
Residue management	Kept	Removed	Kept	Removed
Rotations	M M	M M	M M	M M
	M W	M W	M W	M W
	W M	W M	W M	W M
	W W	W W	W W	W W

W=wheat, M=maize.
Rotation: MM=continuous maize, WW=continuous wheat, WM or MW=yearly rotation of maize and wheat.

The soil quality concept

As a way of further introducing the case study, we will present some soil quality results from the long-term experiment. When evaluating an agricultural management system for sustainability, the central question is: which production system will not exhaust the resource base, will optimize soil conditions and will reduce food production vulnerability, while at the same time maintaining or enhancing productivity? Soil quality can be seen as a conceptual translation of the sustainability concept towards soil. Karlen et al. (1997) defined soil quality for the Soil Science Society of America as "the capacity of a specific kind of soil to function, within naturally managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation." A simpler operational definition is given by Gregorich et al. (1994) as "the degree of fitness of a soil for a specific use." This implies that soil quality depends on the role for which the soil is destined (Singer and Ewing, 2000). Within the framework of agricultural production, high soil quality equates to the soil's ability to maintain a high productivity without significant soil or environmental degradation. Evaluation of soil quality is based on physical, chemical, and biological characteristics of the soil.

A comparative soil quality evaluation is one in which the system's performance is determined in relation to alternatives. When the biotic and abiotic soil system attributes of alternative systems are compared, a decision about the relative sustainability of each system is made based on the difference in magnitude of the measured parameters (Larson and Pierce, 1994). A comparative assessment is useful for determining differences in soil attributes among management practices that have been in place for some period of time (Wienhold et al., 2004). A dynamic assessment approach differs in that the dynamics of the system form a meter for its sustainability (Larson and Pierce, 1994). A dynamic assessment is necessary for determining the direction and magnitude of change a management practice is having (Wienhold et al., 2004), especially when compared to the common, existing farmer practices. This assessment normally involves an adequate time frame.

A minimum set of soil characteristics that represents soil quality must be selected and quantified, to be able to apply any evaluation assessment and proceed from a theoretical definition to a measurement of soil quality (Larson and Pierce, 1991; Gregorich et al., 1994). Different authors have proposed several minimum data sets. We propose that instead of working with predefined lists of indicators, that indicators be selected based on the site-specific agro-ecological conditions by comparing optimal conditions for the specific land use with the real conditions. This comparison would reveal the limiting factors of the system. All parameters related to these limiting factors would be measured in a first overall evaluation. Based on the obtained results, we could thereafter refine the list of relevant parameters and come up with a minimum data set for future assessments (Govaerts et al., 2006a).

Soil quality in Mexican highlands' case study

In order to apply the concept of soil quality, one must have a defined set of indicator parameters for what to measure. As discussed, several minimum lists of indicators can be found in literature. The approach used for this case study, however, was different. We did not utilize the so-called generally predefined minimum data sets (Larson and Pierce, 1994), but instead utilized an agro-ecological site-specific selection of indicators as described above, which led to a two-step-approach. The first step was the set up of a limiting factor parameter list, based on a comparison of the optimal conditions for the land-use and the actual agro-ecological characteristics. Indicators related to the limiting factors will possibly be relevant for the evaluation of the system and form the limiting factor parameters. The second step was the selection of the most explicative indicators from the set of measured indicators to form the eventual strict minimum data set.

Table 2 shows the results of the comparison of the optimal conditions with the actual situation at the CIMMYT station at El Batán in the central Mexican highlands. Table 3 lists the limiting factor parameters, which were evaluated by measuring the following indicators:

- Physical: small ring infiltration, direct surface infiltration, aggregation by wet and dry sieving, penetration resistance, cone penetration, probe depth, bulk density, permanent wilting point, field capacity
- Chemical: CEC, total N, NO_3^-, and NH_4^+, total organic C, P, macronutrients (Ca, Mg, K, Na), micronutrients (Fe, Mn, Zn, Cu), pH, EC
- Biological: Microbial biomass C and N

After statistical analysis, the refined soil quality minimum data set included the following physical indicators: time-to-pond, aggregate stability, permanent wilting point, and topsoil resistance. Important chemical indicators were concentrations of C, N, K, and Zn in the 0–5 cm topsoil and C, N concentrations in 5–20 cm.

Multivariate analysis grouped the treatments into clusters: (1) zero tillage with retention of residue; (2) zero tillage with residue removal; and (3) conventional tillage. Zero tillage combined with crop residue retention improved chemical and physical conditions of the soil. In contrast, zero tillage with removal of residues led to high accumulation of Mn in the topsoil, low aggregate stability, high penetration resistance and surface slaking resulting in low time-to-pond values and high runoff. Finally, soil quality under conventional tillage was intermediate (irrespective of residue mangement), especially reflected in the physical status of the soil.

More details on the case study can be found in

Govaerts, B., K.D. Sayre, J. Deckers. 2006a. A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. *Soil & Tillage Research* 87: 163-174.

Table 3. Limiting factor parameter set for the El Batán area (Adapted from Govaerts et al., 2006a).

Parameters
Compaction
Infiltration
Moisture content
Aggregate stability
Bulk density
Organic carbon
Nutrient status
Biological activity
Soil borne diseases

Table 2. Comparison of optimal conditions for crop growth versus El Batán agro-ecological conditions (adapted from Govaerts et al., 2006a).

Parameter	Optimal wheat conditions	Conditions at El Batán	Optimal maize conditions	Conditions at El Batán	Possible limitation
Climate					
Soil temp.		15-22 °C	16-18 °C*	15-22 °C	No
Optimum day temp.	20–25 °C♦	20-25 °C	25-30 °C*	20-25 °C	No
Mean night temp.			>13 °C*		No
Mean day temp.			<45 °C*		No
Rainfall	400-600 mm♦	600 mm Periods of drought Periods of excessive rainfall	400 mm*	600 mm Periods of drought Periods of excessive rainfall	Yes
Soil					
Structure	Fine♦	Clay	Fine*	Clay	No
Water content	Avoid waterlogging, run-off, and starvation	Periods of drought and logging	Avoid waterlogging, run-off, and starvation	Periods of drought and logging	Yes
Aeration	Well-aerated♦	Low compaction, high bulk density, slaking	Well-aerated*	Low compaction, high bulk density, slaking	Yes
Organic matter	High♦	High	High*	High	No
Field capacity			High*	High	No
pH	>5.0♦	5.9	5.0–7.0*	5.9	No
Al-content	Low♦	0	Low*	0	No
Nutrient condition	High♦	Tend to decline	High*	Tend to decline	Yes
Micronutrients	Commonly deficient in Cu, B, Mn, Zn**	Tend to decline	Commonly deficient in Fe, Zn**	Tend to decline	Yes
Pathogen	Pathogen–free	Yellow rust, leaf rust and Septoria tritici	Pathogen-free	Nematode sensible	Yes

♦ Tanner and Raemaeker, 2002; * Ristanovic, 2002; ** Sayre, K. D. personal communication

Further reading
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Doran, J.W., T.B. Parkin. 1994. Defining and assessing soil quality. In: J.W. Doran, D.C. Coleman, D.F. Bezdicek, B.A. Stewart (eds.), Defining soil quality for a sustainable environment. Madison: American Society of Agronomy (ASA) and Soil Science Society of America (SSSA). Pp. 3-21.
Karlen, D.L., D.E. Stott. 1994. A framework for evaluating physical and chemical indicators of soil quality. In: J.W. Doran, D.C. Coleman, D.F. Bezdicek, B.A. Stewart, (Eds.), Defining soil quality for a sustainable environment. Madison: ASA and SSSA. Pp. 53-72.
Larson, W.E., F.J. Pierce. 1994. The dynamics of soil quality as a measurement of sustainable management. In: J.W. Doran, D.C. Coleman, D.F. Bezdicek, B.A. Stewart (Eds.), Defining soil quality for a sustainable environment. Madison: ASA and SSSA. Pp. 37-51.

Using the NDVI handheld sensor to monitor crop growth and development

Crop performance, growth, and development are the integrated evaluators that show the efficiency of the chosen agricultural management system within the boundaries of the agro-ecological environment. Any crop cultivar (that has been selected for the given agro-ecological area), will act as an integrated evaluator of all environmental factors thus showing how management influences and determines resource-use efficiency. Yields can be measured as an end-of-season static result of seasonal crop performance, but these results do not reflect the fluctuations of the crop's performance throughout the season. End-of-season yield results do not permit the evaluation of within-season management interactions with the production environment and do not allow for full understanding of the applied management practice. In order to understand and evaluate cropping systems, and to fine-tune resource management, crop performance over time is a crucial factor. The effect of management factors, such as tillage systems, crop residue management, and crop rotation on crop growth and development during the crop cycle has not been studied intensively. Until now, most of the knowledge on plant growth and development has been developed for conventional management practices, including heavy tillage and common crop residue removal.

The NDVI handheld sensor can be used to follow crop growth and development throughout the season, and thus increases our understanding of the different management practices.

Case study from the Mexican highlands

Materials and methods
NDVI measurements were taken with the GreenSeeker™ Handheld Optical Sensor Unit (NTech Industries, Inc., USA) in the central rows of all plots of the 16 core practices that were studied 3 times a week throughout the 2004 and 2006 growing seasons. The average NDVI values were plotted against time for all treatments. As an example, the NDVI-based growth and development curves for maize in the 2006 growing season are shown (Figure 2). The NDVI curves were analyzed with PROC MIXED (SAS institute, 1994) using the REPEATED statement for the analysis of repeated measurements. The NDVI curves were divided in three periods for the PROC MIXED analysis and the analysis was done separately for each period. The 3 considered periods were: Period I with increasing NDVI values (days 16-66), Period II with relatively stable NDVI values (days 69-94) and Period III with decreasing NDVI values (days 100-136) (Verhulst et al., 2010).

Results
The zero tillage practices with residue retention had lower NDVI values in Period I compared to the conventional tillage treatments with the same rotation ($P<0.05$). Also, rotation seemed to have an influence on early crop development with lower NDVI values for maize sown after wheat than for maize monoculture in Period I (Figure 2). Maize after wheat under conventional tillage with residue retention had lower NDVI values than maize after maize under conventional tillage with residue retention or removal ($P<0.05$). For maize after wheat under conventional tillage when residue was removed, the NDVI was lower as compared to maize after maize under conventional tillage with residue retention ($P<0.05$). There were no differences between crop rotations later in the season. Zero tillage with residue removal and crop rotation had lower values than all other treatments in all three periods ($P<0.05$) (Verhulst et al., 2010).

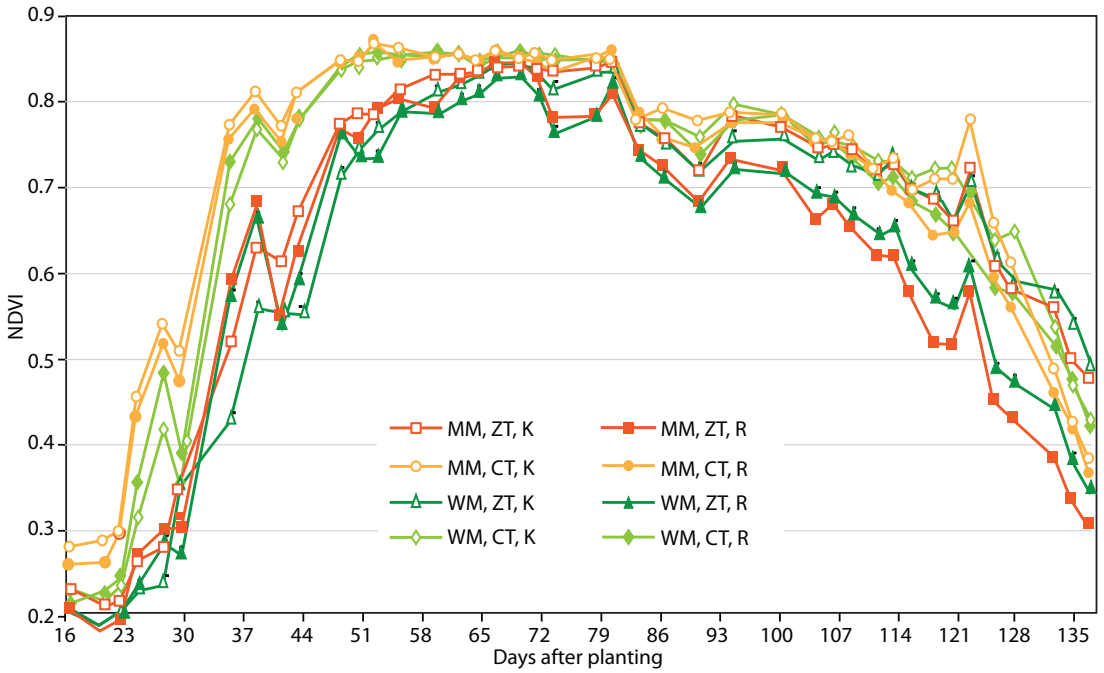
Discussion
Conventional tillage resulted in faster growth compared to zero tillage with residue retention at the beginning of the season. Reports on differences

in crop development under different tillage practices are scarce, but some reports were found that coincide with our findings. Riley (1998) reported that development of spring cereals was delayed with reduced tillage, but this was compensated for later in the season. Raimbault and Vyn (1991) and Vyn and Raimbault (1993) reported that zero tillage resulted in slower plant growth compared to conventional tillage systems. However, McMaster et al. (2002) reported faster, more uniform and greater seedling emergence under zero tillage than in conventional tillage in four out of six years in the Central Great Plains, due to more favorable soil water levels in the seeding zone under zero tillage.

It is important to note that the slower take off in growth with zero tillage compared to conventional tillage is compensated for later in the season. Moreover, when looking at final yield (reported in Govaerts et al., 2005), treatments with higher yields generally achieved their maximum NDVI later in the growing period. This indicates that treatments with an initial slower growth may have an advantage. It seems that zero tillage with residue retention induces a more timely and efficient use of available crop growth resources. It could be hypothesized that the changes in C and N cycling between zero tillage and conventional tillage both with residue retention result in a better synchronization between demand and N mineralization in zero tillage with residue retention, where N is released more slowly as compared to the flush of N released in conventional tillage at the beginning of the season when tillage is applied. However, more research is needed to confirm this hypothesis.

Rotation seemed to have an influence on early crop development with lower NDVI values for crops sown after wheat than for crops sown after maize. No reports were found in literature on wheat slowing down the early crop development of the following crop. Differences between rotations disappeared later in the growing season and growing wheat as the previous crop had no adverse effect on final yield compared to growing maize as the previous crop.

The two management practices that combined zero tillage with residue removal (continuous maize and wheat-maize rotation) were found to be overall low performing when analyzing the NDVI-based crop growth curves. This corresponds with the overall negative impact on soil quality and soil health of these practices (Govaerts et al., 2006a,b; 2007a, b; 2008; 2009) and their low yields (Govaerts et al., 2005).



Crop sequence: MM monoculture of maize, WM yearly rotation of maize and wheat. Tillage system: CT conventional tillage, ZT zero tillage. Residue management: R all residues removed from the field, K all residues kept on the field.

Figure 2. NDVI-based crop growth and development curves (NDVI vs. days after planting) for maize in the 2006 crop cycle in the long-term sustainability trial at El Batán, Mexico (adapted from Verhulst et al., 2010).

It can be concluded that tillage, rotation, and residue management practices influence crop development. However, more research is needed to fully understand the underlying mechanisms. As most practices and knowledge are currently based on conventionally tilled cropping, it is important to monitor and understand crop growth under different management systems to select the right varieties and adjust timing and practice of input supply (fertilizer, irrigation, etc.) in a holistic way for each system.

More details on the case study can be found in

Verhulst, N., B. Govaerts, K.D. Sayre, P. De Corte, J. Crossa, J. Deckers, L. Dendooven. 2010. The effects of tillage, crop rotation, and residue management on maize and wheat growth and development evaluated with an optical sensor. *Field Crops Research* (Submitted).

Further reading

Raimbault, B.A., T.J. Vyn. 1991. Crop-Rotation and Tillage Effects on Corn Growth and Soil Structural Stability. *Agronomy Journal* 83: 979-985.

Riley, H.C.F. 1998. Soil mineral-N and N-fertilizer requirements of spring cereals in two long-term tillage trials on loam soil in southeast Norway. *Soil & Tillage Research* 48: 265-274.

Vyn, T.J., B.A. Raimbault. 1993. Long-Term Effect of 5 Tillage Systems on Corn Response and Soil-Structure. *Agronomy Journal* 85: 1074-1079.

Spatial variability in crop performance as an indicator of sustainability

The spatial structure of ecosystems often reflects how these systems function (Herrick et al., 2002). The spatial ecosystem structure reflects the spatial distribution of the key production-related processes. A change in spatial variability in plant performance on any scale indicates that the distribution of limiting resources has changed or that another resource has become limiting. This may reflect a change in the processes that both control and are affected by the availability of resources on that scale. When all plant-growth elements are abundantly available, a uniform pattern of plant growth will be seen. However, when one or more critical plant elements are limiting, plant-to-plant competition effects will increase plant-to-plant performance variability, increasing the coefficient of variation (CV) compared with a system where no elements are limiting.

As a general principle, we propose that competition for resources results in greater within-plot plant-to-plant variability. Although scarce, there are some reports that support this principle. In a study of maize growth evolution, the onset of intra-specific competition was inferred from an increase in the CV of plant biomass. Edmeades and Daynard (1979) reported that at a low density (5 plants per meter), the CV of plant biomass had a low and almost constant value (ca. 10%) during the whole growing season, indicative of a similar growth of each individual plant within the stand. Contrarily, at a high plant population of 20 plants per meter, the CV increased to 40% during the same period. This statistical parameter can therefore reveal the existence of plants with different competitive abilities within the same stand density (Edmeades and Daynard, 1979). The onset of this hierarchical growth pattern among plants within a stand would be related to the intensity of intra-specific competition, i.e. plant population density (Maddonni and Otegui, 2004). Comparing different improved maize hybrids, Tollenaar and Wu (1999) concluded that crop resource-use efficiency is inversely related to plant-to-plant variability. Martin et al. (2005) suggested competition for soil moisture as a source of increased plant-to-plant variability, especially in dryland fields.

Within-plot spatial variability can be the result of inherent variation in plot conditions. However, agronomical practices also influence spatial within-plot plant variability. Increased within-plot plant spatial variability throughout the season can therefore be considered a reaction to inefficient use of critical plant growth resources provoked by an unsustainable management of these resources. Ginting et al. (2003) reported that differences in soybean yield between high and low elevation were larger for a conventional tillage system compared to a reduced tillage system. Kravchenko et al. (2005) compared a zero-input with a low and conventional input treatment, and found that the overall variability (expressed by CV) was the highest in the zero-input treatment and that crop yields of the same treatment were more sensitive to small-scale variations in nutrient and water availability conditions of the field.

Spatial variability reduces resource-use efficiency: the potentials in climate conditions and germplasm are expressed only in certain parts of the plot, while in others, crop yields lag behind. Increased plant spatial variability throughout the season can

therefore be considered a reaction to inefficient use of critical plant growth resources induced by an unsustainable management of these resources. As such, it can serve as a sound indicator of crop mismanagement and can help to correct this. The GreenSeeker™ NDVI sensor can be used as a tool to follow the spatial variability in crop performance throughout the season.

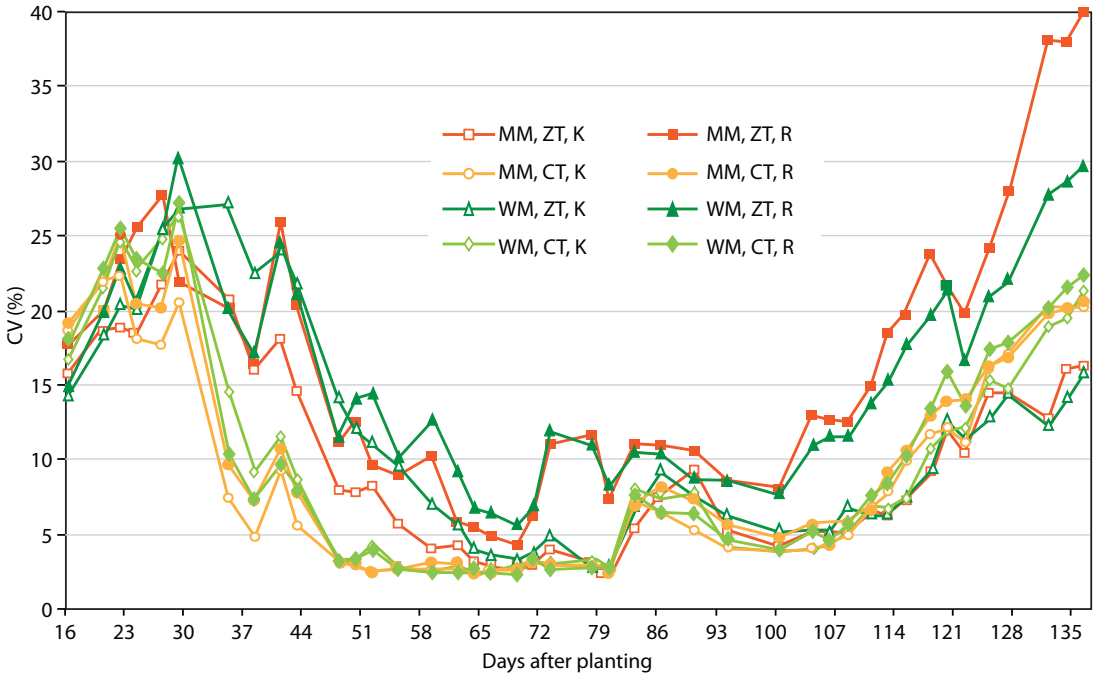
Case study from the Mexican highlands

Materials and methods

NDVI measurements were taken in the same way as the measurements of the crop development study in the 2004, 2005, and 2006 growing seasons. The CV is defined as the standard deviation expressed as a percentage of the mean result (Steel et al. 1997). The CV was calculated for each NDVI measuring sequence per plot that consisted of approximately 200 individual measuring points throughout the plot. As an example, the CVs corresponding to the maize growth curves (CV vs. days after sowing) from the 2006 growing season are shown (Figure 3). The CVs of the NDVI calculated from the measurement tracks measured several times during the growing season were analyzed as dependent variables with PROC MIXED using the REPEATED statement for the analysis of repeated measurements in time.

Results

The CV curves showed a general trend opposite to the one observed in the NDVI curves (Figure 2). There was high spatial variability at the beginning of the season for all treatments. After this initial stage, the canopy began to close and the CV declined (until approximately 65 days after planting). Soil coverage by the canopy was then near maximum, with a uniform leaf color, and a CV of <10%. Around tasseling (83 days after planting), CVs increased again. The CVs decreased more slowly under zero tillage than under conventional tillage but later in the season (around 70 days after planting) there were no differences between zero tillage with residue retention and conventional tillage treatments. The MIXED procedure revealed that continuous maize under zero tillage with residue removal resulted in significantly higher CVs throughout the season than all other treatments ($P<0.05$). Use of zero tillage with residue removal and maize in rotation with wheat provided significantly lower CV values than the same treatment with continuous maize, but significantly higher CVs compared to all other treatments ($P<0.05$) (Govaerts et al., 2007c).



Crop sequence: MM monoculture of maize, WM yearly rotation of maize and wheat. Tillage system: CT conventional tillage, ZT zero tillage. Residue management: R all residues removed from the field, K all residues kept on the field.

Figure 3. Coefficient of variation (CV) corresponding with the NDVI-based growth curve (CV vs. days after sowing) for maize in the 2006 crop cycle in the long-term sustainability trial at El Batán, Mexico (adapted from Govaerts et al., 2007c).

Discussion

Measurements of CV throughout the crop season reflected the growth and senescence curve of maize (Figure 3). Once the canopy began to close, leaves from larger plants covered the leaves and whorl of smaller plants, extending further into the linear row. As these leaves began to fill the row, intersecting with, and in some cases covering up leaves from smaller plants, soil coverage increased the amount of green vegetation. Comparable results were obtained by Raun et al. (2005).

There were significantly higher CVs throughout the season in the sustainability trial for both maize grown in monoculture as well as in rotation with wheat when planted with zero tillage and residue removal ($P<0.05$). All plots managed with one of these treatments showed higher CVs throughout the season and as such higher within-plot variability. These same treatments have been characterized by low yields (up to 50% yield loss) in all past years of the experiment, compared with zero tillage with residue retention (Govaerts et al., 2005). The same two treatments were also characterized by low soil quality and bad soil health compared with other treatments (Govaerts et al., 2006b; 2007a,b; 2008). When the experiment was started in 1990, soil variability was mapped and was found to be minimal within the experiment area (Lopez-Noverola, 1995). Consecutive years of mismanagement (zero tillage with residue removal) increased the spatial variability in plant performance in two ways. Firstly, it changed values of soil properties to such an extent that they caused stressful conditions. Stressful conditions increase plant-to-plant competition for resources and this competition results in greater plant variability (Martin et al., 2005). Secondly, management affected the variability characteristics of soil properties. Due to variation in topographic factors, the degradation caused by the mismanagement did not occur in an equally distributed way throughout the field. This resulted in spatial variability of soil characteristics which in turn caused spatial variability in crop performance. Zero tillage with residue retention resulted in better water infiltration and soil fertility throughout the plot, avoiding soil degradation as well as reducing plant competition and as such spatial variability. It can be concluded that increased within-plot spatial variability in crop performance was associated with incorrect agronomic management, in this case the zero tillage treatments with residue removal that were characterized by a reduced biological, chemical, and physical soil quality.

More details on the case study can be found in

Govaerts, B., K.D. Sayre, J. Deckers, P. Decorte, B. Goudeseune, K. Lichter, J. Crossa, L. Dendooven. 2007. Evaluating spatial within plot crop variability for different management practices with an optical sensor? *Plant and Soil* 299: 29-42.

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Using spatial variability in crop performance (NDVI) to evaluate soil processes determining the system sustainability

Spatial variability in crop performance integrates the effects of spatial variability in soil, above-ground environment, and plant characteristics (Stafford et al. 1996). Differences in resources only result in spatial variability in crop development when the resource is limiting crop performance. Shatar and McBratney (1999) examined relationships between sorghum yield and soil properties in Australia and found that most of the measured soil properties varied spatially, but only a few were responsible for variation in yield. Along the boundaries of the field, the major cause of variation in sorghum yield was changes in plant-available water. Soil within the centre of

the field held more water so that yield production reached a level at which the potassium content was inadequate and limited production. Machado et al. (2002) reported a positive effect of soil NO_3-N on sorghum grain yield in a year when water was abundant, but a negative effect in a year when water was limited.

Linking spatial variability in crop performance to differences in soil attributes could identify the limiting factors driving the system. Patterns of crop performance will follow the spatial variability of the underlying limiting soil attributes. The sensor detects 'cold and hot zones' of plant performance, which can be correlated to field spots of differing soil quality. This allows a detailed investigation of underlying soil processes and how they might be affected by different management practices.

Case study from the Mexican highlands

Materials and methods

NDVI measurements were taken as a measure of plant performance with the GreenSeeker™ Handheld Optical Sensor Unit (NTech Industries, Inc., USA) 84 days after planting in the 2006 crop cycle (the beginning of tasseling for maize and the beginning of grain filling for wheat). For maize, NDVI was measured in all rows, except border rows, giving a total of eight rows. For wheat, we measured 6 strips that were 0.60 m wide, with the first and last one at 1.0 m from the border and the remaining ones at equidistance. Soil attributes were only measured spatially in plots with crop rotations of maize and wheat (8 treatments). Soil attributes were determined in 8 points within each plot, lying on a grid of 5.5 by 2.5 m, leaving a border of 3 m at the south-east side of the plot and a border of 2.5 m at all other sides. The following soil attributes were measured: volumetric soil moisture content; direct surface infiltration (time-to-pond); aggregate distribution and stability by dry and wet sieving; and total N, organic matter, pH, electrolytic conductivity, content of Ca, Mg, Na, K, and inorganic N. To examine the within-plot patterns of crop performance under the different treatments, maps of NDVI were produced using ArcMap software, version 9.2 (Environmental Systems Research Institute 2006). To link the patterns in plant performance visually to the variability in soil attributes, overlays of NDVI and soil attributes were made with ArcMap 9.2. As an example, the overlay figures are shown for maize for some key soil attributes (Figure 4). In the overlay figure only one plot was chosen to represent both conventional tillage with residue removal and incorporation, as the effect of residue was minimal under conventional tillage.

Results

There was a clear pattern in crop performance for maize with zero tillage and residue removal (Figure 4), which was not observed in the surrounding plots. Low values were found at the south-east side of the field (light colors) and high values at the north-west side (darker colors). In plots under zero tillage with residue removal, soil moisture content, time-to-pond, and soil aggregate distribution, expressed as mean weight diameter (MWD) obtained through dry sieving and organic matter content at 0-5 cm, varied from low values at the south-east side of the field to high values at the north-west side, reflecting the pattern in crop performance (Figure 4). Higher values were observed for the same soil attributes under zero tillage with residue retention than under conventional tillage (Figure 4). Plots under zero tillage with residue retention or conventional tillage did not have a pattern of soil attributes nor in crop performance. Maps of inorganic N content showed a clear pattern under zero tillage with residue removal in the 0-5 cm layer (Figure 4). Inorganic N ranged from high values at the south-east side of the field and toward low values at the north-west side, the opposite of what was observed for crop performance.

Discussion

Soils under zero tillage with residue removal did not have a mulch layer that slowed down run-off and absorbed water. The poor structure resulted in fast surface sealing, low infiltration rates, high run-off, and soil erosion (Govaerts et al., 2006a). Small variations in topography (field slope <0.3%) induced differences in degradation at different places in the field. Although a slope of 0.3% is small, the water in the zero tillage with residue removal flowed toward the lowest points (in this case the north-west side of the field) because the soil was unprotected and the topsoil was sealed. As such, the north-west side of the field had improved access to soil water due to the run-off from the more elevated south-east side, which partly compensated for the general soil quality degradation caused by zero tillage with residue removal.

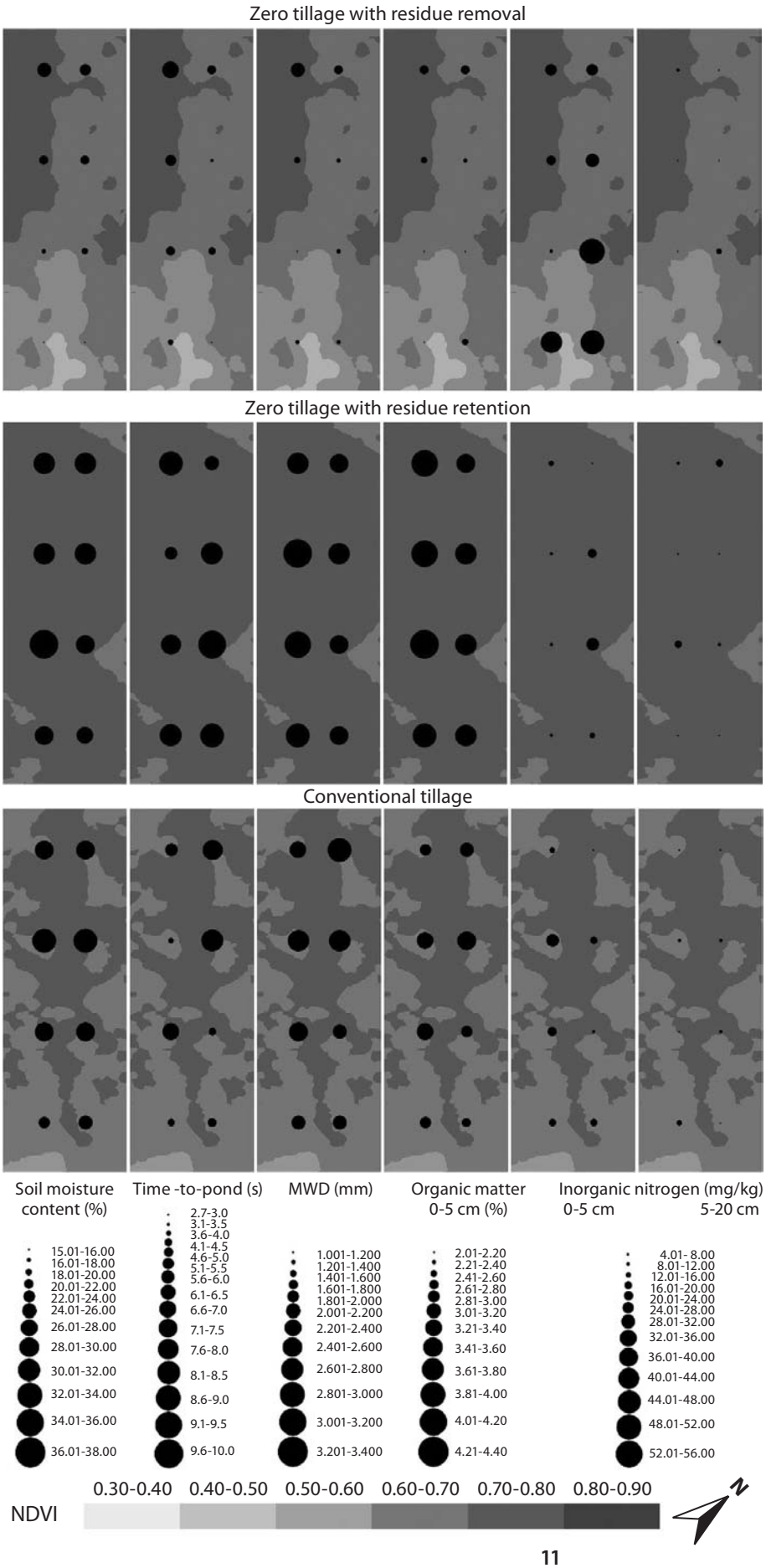

Figure 4. Overlays of NDVI and soil attributes (volumetric soil moisture content (%), time-to-pond, mean weight diameter obtained through dry sieving (mm), soil organic matter (%), inorganic nitrogen content (mg per kg) in the 0-5 cm and the 5-20 cm layer) for maize plots in 2006 at CIMMYT's long-term sustainability trial, El Batán, Mexico (adapted from Verhulst et al., 2009).

When water is the limiting factor, more available water makes the plants grow better, resulting in higher within-season NDVI levels and higher end-of-season crop and root biomass at the north-west side compared to the south-east side of the field. After harvest, more remnant stubble and root was left on the field at the north-west side. This caused organic matter levels—and consequently soil structure, retention of water by organic matter, and infiltration—to remain higher at the north-west side of the field than at the south-east side under zero tillage with residue removal. In that way soil water content at the north-west side improved further compared to the south-east side and consequently plant growth and crop performance were better at the north-west side. Over the years, this incorrect agronomic management, i.e. zero tillage with residue removal, increased the spatial variability in soil properties and crop performance since spatial variability was low in the field when the experiment was started (Lopez-Noverola, 1995).

The variability in soil attributes induced spatial variability in crop performance: under zero tillage with residue removal, soil quality and crop performance followed micro-topography with higher values where elevation was lower. Apart from that, the general soil quality degradation under zero tillage with residue removal caused stressful conditions. As stated previously, stressful conditions increase plant-to-plant competition for resources and this competition results in greater plant variability (Martin et al., 2005). The zero tillage practice with residue removal caused a non-uniform distribution of crop performance within the field, indicating the inefficient use of available resources with consequent yield losses, since in some parts of the field a higher yield was achieved than in others within the specific conditions of climate and germplasm.

Maps of plots under zero tillage with residue retention contrasted sharply with those of plots under zero tillage with residue removal. The soil moisture content, infiltration (time-to-pond), soil structure (MWD obtained through dry sieving), and organic matter content were uniformly high under zero tillage with residue retention (Figure 4), whereas zero tillage with residue removal showed higher values where elevation was lower. The lack of the effect of topography in residue-retained systems is a consequence of the impedance of run-off due to the presence of a mulch layer (Govaerts et al., 2006a) and a commensurate reduction in the evaporative loss of soil water (Scopel et al., 2004). Both increased the amount of water available for the crop, ensuring an even crop performance throughout the field. The high soil quality reduced competition for resources and in that way plant variability. Values and variability for soil attributes and crop performance were intermediate under conventional tillage.

The foregoing shows that crop performance followed the same pattern as soil moisture and related attributes, such as infiltration, soil structure, and organic matter. Thus, soil moisture is the system's limiting factor. To develop sustainable management practices for this target zone, moisture capture and storage must be optimized. The intermediate soil quality under conventional tillage could cause problems in dry years when soil water conservation is crucial to avoid stress.

More details on the case study can be found in

Verhulst, N., B. Govaerts, K.D. Sayre, J. Deckers, L. Dendooven. 2009. Using NDVI and soil quality analysis to assess influence of agronomic management on within-plot spatial variability and factors limiting production. *Plant and Soil* 317: 41-59.

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