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Analyzing the effects of climate variability on spatial pattern of yield in a maize–wheat–soybean rotation

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Abstract

The identification of homogeneous management zones within a field is crucial for variable rate application of agronomic inputs. This study proposed a methodology to identify homogeneous management zones within a 8 ha field, based on the stability of measured and simulated yield patterns in a maize–soybean–wheat crop rotation in north-east Italy. Crop growth and yield were simulated over a 14-year period (1989–2002) using *CERES-Maize*, *CROPGRO-Soybean* and *CERES-Wheat* models to account for weather effects on yield spatial patterns. The overlay of long-term assessments of yield spatial and temporal data allowed for the identification of two stable zones with different yield levels, one with greater yield (called HS for high and stable yield) and one with lower yield (called LS for low and stable yield). The size of the HS zone identified using 14 years of simulated yield was smaller than the one obtained when considering only yield monitor data taken during the 5-year crop rotation. The LS zone was larger when using simulated data, confirming that the consistency of temporal stability increased by increasing the years considered. The models were able to closely simulate yield across the field when site-specific inputs were used, showing potential for use in yield map interpretation in the context of precision agriculture. Results showed that a combination of GIS tools and crop growth simulation models can be used to identify temporally stable zones, which is a fundamental prerequisite for adopting variable rate technologies.

Keywords: Crop simulation model; Maize; Management zones; Soybean; Yield spatial variability; Yield temporal stability; Wheat

1. Introduction

Production fields have been traditionally considered a homogeneous unit despite the presence of spatial variability of numerous factors (e.g. soil properties and attributes, nutrient availability) within a field. Uniform agronomic management where there is spatial variability is inefficient both in terms of environmental impact and production costs (Pierce and Nowak, 1999). Alternative crop and soil site-specific management proposed by precision agriculture gives farmers the opportunity to increase benefits by improving yield and/or by reducing inputs and minimizing environmental impact (Robert, 1993, 2002). Site-specific management (SSM) strategies may be able to optimize production, but their potential benefits are highly dependent on the accuracy of the assessment of such variability (Pierce and Nowak, 1999).

Yield rates vary spatially and maps produced by the yield monitor systems are evidence of the degree of within-field variability. The magnitude of this variability is a good indication of the suitability of implementing a spatially variable management plan. Yield maps are of little value until they are analyzed and interpreted leading to some changes in management in response to the observed variability. We are inundated with information regarding crop yield and factors that affect it, but we are still not able to interpret the yield variability across a field. Data from yield monitors have shown that very large yield differences commonly exist within a field (Basso et al., 2001; Batchelor et al., 2002; Brock et al., 2005), and that patterns of yield variability within a field differ from year to year (Pierce and Nowak, 1999). Remote imagery confirms large differences in canopy development that lead to yield variability (Basso et al., 2004). However, evidence of producers developing innovative management strategies that capitalize on variability has been anecdotal at best. Interpretation of the information contained in a yield map and assessment of the manageable variability according to technical and economic aspects is not always clear to farmers

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(Cassel et al., 2000; Pringle et al., 2003). A proper assessment of yield variability is obtained only by considering several years with different crops (Joernsgaard and Halmoe, 2003) because the same limiting factor can exert different spatial and temporal influence on yield (Machado et al., 2002). McBratney et al. (2005) in their paper describing the future directions of precision agriculture pointed out that temporal variation receives insufficient recognition.

A management zone for variable rate technology (VRT) can be defined as a sub-region of a field that expresses a near-homogeneous combination of yield limiting factors for which a single rate of a specific crop input is appropriate (Doerge and Gardner, 1999). Various authors have proposed criteria for the delineation of management zones (Mulla, 1991; Ferguson et al., 2004; Schepers et al., 2004; Chang et al., 2004). Inman et al. (2005) found that landscape position alone was not effective in dividing fields into units for variable rate nitrogen N management. Franzen et al. (2002) concluded that topography-based zone soil sampling may be useful in semiarid environments. Ostergaard (1997) developed management zones for N VRT application based on soil type, yield, topography, aerial photos and producer experience. Fleming et al. (2001) described the application of soil color (SC) and farmer knowledge to define management zones for variable rate fertilizer applications. Fridgen et al. (2004) developed a software program called Management Zone Analyst (MZA) that used a fuzzy *c*-means unsupervised clustering algorithm that assigns field information into like classes or potential management zones.

Determining the optimum prescription for a location within a field is challenging. The biggest challenge is that the plant response to variable management levels is often highly dependent upon the weather that occurs during the season. For instance, high population may be optimal for maximizing net return for a hilltop within a field in a wet year, while a very low population may be optimal in a dry year. The producer, however, must make a decision about population level at planting time, without knowledge of the weather that will be encountered during the season. Since future weather is unknown, a risk management strategy must be employed to determine the prescription that satisfies the objective as a function of a sufficiently long period of time (i.e. 30 years) to represent the diversity of environments that may be encountered. The biggest challenge of this strategy is the development of an appropriate yield response function that can represent the plant's response to the variable rate management and the response to other interactions. Simple statistical functions that relate yield response to nitrogen rate or population do not sufficiently account for temporal interactions of weather and stress on yield response to management. Process oriented crop simulation models, such as the CERES and CROPGRO models (Ritchie and Otter, 1985; Boote et al., 1998), integrate the effects of temporal and multiple stress interactions on crop growth processes under different environmental and management conditions.

It is rather obvious that crop simulations cannot be performed everywhere in a field given that the cost and the availability of detailed inputs would be prohibitive. A more balanced approach to the application of crop simulation models to precision agriculture would be to delineate zones within the field of similar crop performance. Several strategies have been proposed to apply crop models for spatial and temporal analysis. They varied from point-based approach (Booltink et al., 2001) to grid-based simulation (Batchelor et al., 2002) and to previously determined management zones through remote sensing (Basso et al., 2001). An additional approach may be to consider the temporal stability of spatial variability of measured yield maps to delineate stable or unstable spatial patterns. Model validation can be then be performed at selected sites within these delineated management zones. Even though crop models have shown high potential for optimizing production and minimizing environmental impact, limited studies report the usefulness of crop models for spatial applications in precision agriculture (Cora et al., 1999; Paz et al., 1999; Basso et al., 2001; Fraisse et al., 2001; Batchelor et al., 2002; Miao et al., 2006). No studies were found in the literature hitherto that used crop models to assess consequences of climatic variability on spatial variability of yield and to use such knowledge to properly delineate management zones that are stable over time.

The objectives of this study were: (i) to develop a methodology by combining measured historical spatial yield data and simulation modeling to assess spatial and temporal variability of yield in wheat, maize and soybean; (ii) to analyze the effects of 14-year climate (i.e. temporal) variability on yield of wheat, maize and soybean using crop models for delineating spatially accurate and temporally stable management zones and to use such knowledge to optimize agronomical management strategies.

2. Materials and methods

2.1. Site description

The study was carried out on a 8 ha field with near zero slope, located close to Rovigo (44°4′12″N, 11°47′22″E, 6 m a.s.l.), NE Italy, during a 5-year crop rotation (1998–2002). The soil type was clay according to the USDA particle-size distribution limits, defined as FAO Ombric and Thionic Histosols. The climate of the area (data relating to the 1989–2002 period) was characterized by an average annual rainfall of 700 mm, distributed mostly in autumn and spring. The annual average temperature was 13.3 °C, with a monthly maximum of 23.5 °C in July and a minimum of 3.2 °C in January. Growing season rainfall for maize (April–September), soybean (March–October) and wheat (November–June) is shown in Fig. 1.

2.2. Agronomic management

The crop rotation adopted consisted of maize (*Zea mays*, L.) in 1998 and 2000, soybean (*Glycine max*, L.) in 1999 and 2002, and wheat (*Triticum aestivum*, L.) in 2001. The agronomic practices applied to the crop generally consisted of minimum tillage and integrated weed control strategies. The specific agronomic practices adopted during the crop rotation are summarized below for each crop.

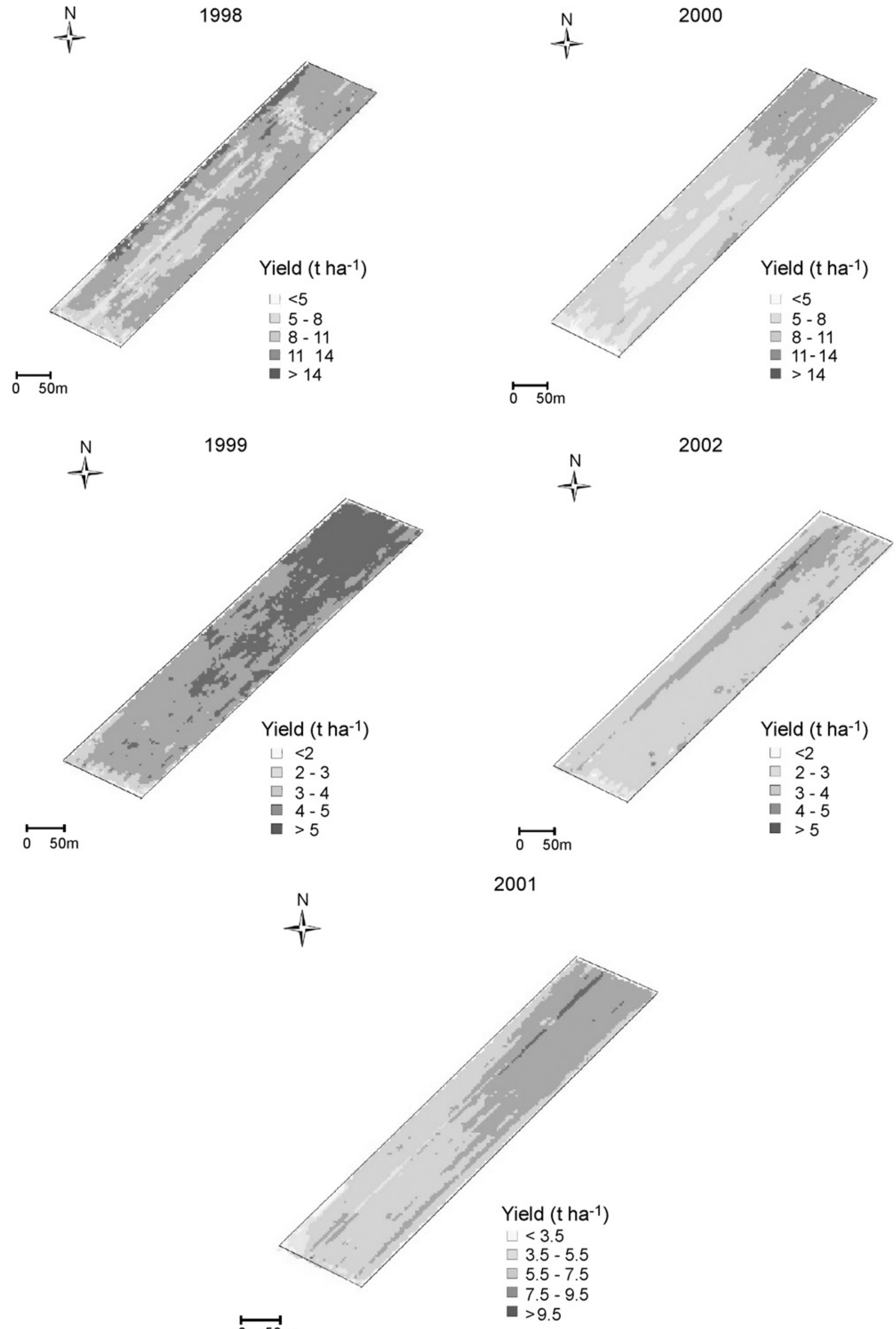

Fig. 1. Yield maps reporting the yield pattern obtained over different growing seasons for the same crop (1998 and 2000: maize; 1999 and 2001: soybean; 2002: wheat).

2.2.1. *Maize*

In 1998, the field was tilled in August to incorporate organic fertilizer (112 kg N ha^{-1}, 37 kg P ha^{-1} and 150 kg K ha^{-1}) applied with a manure spreader. In 2000, tillage practices were done in October. *Pregia* (in 1998) and *PR34F02* (in 2000) hybrids were sown with a planter (0.75 m rows) using seeding rates of 28.4 and 37.3 kg ha^{-1} of seeds (8.1 plants m^{-2}) in 1998 and 2000, respectively. In 1998, mineral fertilizer (57 kg P ha^{-1} and 63 kg K ha^{-1}) was applied preplant and after sowing, 185 kg N ha^{-1} was applied in May. In 2000, 44 kg P ha^{-1} was applied preplant with nitrogen applications of 85 kg N ha^{-1} applied on April 21 and 74 kg N ha^{-1} applied on May 11. Maize was harvested at maturity on September 18 and August 23 in 1998 and 2000, respectively.

2.2.2. Soybean

In 1999, soil tillage was performed on September 19 and November 24 and in 2002, on July 2 and September 21. In both years, seedbed preparation was performed in March to reduce weed emergence. *Loria* (in 1999) and *Bio-Nikir* (in 2002) cultivars were sown with a planter (0.75 m rows) on April 26 and May 30, in 1999 and 2002, respectively. The seeding rate was 59 and 49.5 kg ha^{-1} of seeds (35 and 30 plants m^{-2}) in 1999 and 2002, respectively. Only in 1999, 50 kg P ha^{-1} and 50 kg K ha^{-1} were applied in November. Harvest was carried out on September 27 and October 10 in 1999 and 2002, respectively.

2.2.3. Wheat

The seedbed was prepared in September 2000 with a rear mounted disk harrow at a depth of 20 cm. *Amarok* variety was sown with a grain drill on October 23, at a 204 kg ha^{-1} seeding rate (approximately 450 seeds m^{-2}). The field was fertilized with a 50 kg P ha^{-1} preplant application and three additional N applications during the season (45 kg ha^{-1} on February 17 and March 12, and 136 kg ha^{-1} in April). The crop was harvested on June 25.

2.3. Yield monitoring

Yield data were recorded by using a *New Holland* TX 64 combine equipped with a yield monitor system (grain mass flow and moisture sensors). Site coordinates for each yield measurement were determined with a differentially corrected (*OMNISTAR* signal) Trimble 132 receiver. The SMS software version 3.0^{TM} (AgLeader Technology, Inc.) was used to read the row yield data (expressed at 14% dried matter). After downloading, yield data were cleaned by removing yield values less than 0.5, 0.1 and 0.25 t ha^{-1} or greater than 16, 7 and 10 t ha^{-1} for maize, soybean and wheat, respectively, after careful evaluation of yield distribution and level attained in the studied area. Yield data semivariograms were created using GS+ software version 3.1^{TM} (Gamma Design Software, 1999).

2.4. Methodology for identification of management zones

The identification of homogeneous management zones was carried out by considering the level of yield obtained within the field and the degree of stability over the years (Blackmore, 2000). In particular, the spatial variability of yield was analyzed in ArcView version 3.2^{TM}, by calculating the relative percentage difference of yield crop from the average yield level obtained within the field at each point mapped, according to the following equation [Eq. (1)]:

$$\bar{y}_i = \frac{1}{n}\sum_{k=1}^{k=n}\left[\frac{y_{i_k} - \bar{y}_k}{\bar{y}_k} \times 100\right], \tag{1}$$

where $\bar{y}_i$ is the average percentage difference at location i, $\bar{y}_k$ the average yield (t ha^{-1}) obtained for the complete field at year k, y_{i_k} the yield (t ha^{-1}) monitored at location i at year k, k the single year of the studied period (1998–2002) and n is the number of years of the studied period.

The final map of the zones with different yields was created by overlaying the single map of the relative percentage difference of yield. Different zones were then classified in relation to a relative percentage difference threshold of 100%: the zones for which this value was greater were classified as the zone with high yield, while the zones for which this value was lower were defined as the zone with low yield. To overcome the limits of the coefficient of variation (Pringle et al., 2003), the temporal variability of yield patterns, expressed as degree of stability, was calculated as temporal variance (yield value recorded at each point mapped minus the field mean) according to the method proposed by Blackmore et al. (2003), based on the following equation [Eq. (2)]:

$$\bar{\sigma}_i^2 = \frac{1}{n}\sum_{k=1}^{k=n}(y_{i_k} - \bar{y}_{i_n})^2, \tag{2}$$

where $\bar{\sigma}_i^2$ is the temporal variance (t ha^{-1})^2 value at location i, y_{i_k} the yield (t ha^{-1}) monitored at location i at year k, $\bar{y}_{i_n}$ the average yield over the n years, k the single year of the studied period (1998–2002) and n is the number of years of the studied period.

The temporal variance may vary considerably within a field by slightly changing the threshold used to determine the stable zone, as reported by Blackmore (2000). In this case, a limit value of 1 or 2 t ha^{-1} was considered too low for identifying a homogeneous zone within a field due to the limitation of the farmer to practically manage the land (data not shown). To identify practical and manageable zones, a 2.5 t ha^{-1} threshold was considered reasonable for the conditions studied. By overlaying the map of relative percentage difference with the one of temporal variance, high and stable yield zones (HS) were identified. Conversely, zones characterized by temporally stable and low yield were defined as LS zones. The parts of the field characterized by unstable yield, despite their values, were classified as unstable (U) and were not considered in the analysis.

2.5. Crop growth model description

Simulation runs were performed using the *CROPGRO* model for soybean (Boote et al., 1998) and the *CERES* model for maize (Jones and Kiniry, 1986) and wheat (Ritchie and Otter, 1985). The models are parts of the DSSAT 3.5 (*Decision Support System for Agrotechnology Transfer*) (Hoogenboom et al., 1994). The models are process-oriented models that simulate plant growth and development responses to environmental conditions (soil and weather), genetics and management strategies. The model performance was evaluated using the root mean square error (RMSE) [Eq. (3)]:

$$\text{RMSE} = \left[\frac{1}{n}\sum_{i=1}(y_i - \hat{y}_i)^2\right]^{1/2} \tag{3}$$

where y_i are the measurements, $\hat{y}_i$ the predictions and n is the number of comparisons.

The weather data used by the models included daily values of incoming solar radiation (MJ m^{-2} day^{-1}), maximum and min-

Table 1
Average soil properties (texture and organic matter) measured along soil profile for HS (stable with high yield) and LS (stable with low yield)

Area	Soil properties (%) for different layers											
	0–15 cm				15–30 cm				30–45 cm			
	Clay	Sand	Loam	OM	Clay	Sand	Loam	OM	Clay	Sand	Loam	OM
HS	39	25 a	35 bc	3.73 a	38	24 a	38 b	3.71 a	40	21	39	3.61 a
LS	41	14 b	45 a	2.39 b	41	14 b	45 a	1.81 bc	44	15	41	1.89 b

Different letters (a–c) indicate significant differences between soil properties for the same depth layer (LSD test, $P \leq 0.05$).

imum air temperature (°C) and rainfall (mm). The measured weather data were provided by the Meteorological Centro of Teolo (Arpav) located 20 km away from the study area. Soil input data (sand, silt and clay content, bulk density, organic carbon and water limits) were determined after collecting soil samples at 35 locations at 3 soil depth layers (0–15, 15–30 and 30–45 cm) with a composite sampling scheme using an undisturbed soil core sampler. Soil water limits were calculated using the procedure suggested by Ritchie et al. (1999). To minimize the RMSE values for the complete field and obtain an average percentage difference between simulated and measured values of yield within the stable zone identified for the 5-year crop rotation, model validation was performed according to the measured soil conditions (Table 1).

Spatial and temporal variability of yield for the period (1989–2002) were determined separately for different crops, according to the method previously described and to increase the consistency of the estimation (Bjarne and Steffen, 2003). For each crop, specific thresholds were defined, according to the general objective of minimizing temporal variance and to the higher number of years examined. For maize and wheat, a threshold value of 10% was used to identify the zone having yield greater than the long-term average value – i.e. yield 10% greater than average value – while yield values ≤10% spatial variability were classified as lower yield. Thresholds of ±2.42 and ±1.40 t ha^{-1} were calculated as the average variance affecting yield over years and were used to identify zones being characterized by temporal stability over years for maize and wheat, respectively. For soybean, thresholds of 20% and ±0.84 t ha^{-1} were used for identifying spatial and temporal pattern, respectively. By overlaying the map of relative percentage differences and that of temporal variance, zones characterized by stable yield with high or low yield levels were defined as long-term HS or LS zone. After developing a map of stable patterns for each crop, the maps were overlaid to identify a long-term stable map. Statistics and ANOVA multivariate analysis were developed in SAS version 8.0 (SAS Institute Inc., 1999).

3. Results and discussion

3.1. Spatial and temporal analysis of measured yield data

Crop yields were different between growing seasons for the same crop (Table 2). Intra-year spatial variability was detected, as shown by the yield maps collected with the yield monitor system (Fig. 1). The mean yield was statistically different in different growing seasons. The average maize yield in 2000 was 14.6% (1.64 t ha^{-1}) lower than that monitored in 1998 while, for soybean in 2002, the average yield obtained was 20% (0.97 t ha^{-1}) lower in comparison with that monitored in 1999 (Table 2). For wheat, the average production monitored was slightly lower than the average value generally obtained by the farm. The intra-year variation of yield was appreciable, as indicated by values of both the range of yield and the coefficient of variation, especially for maize with respect to the others crops. The CV calculated ranged from a minimum of 11.69% for soybean in 1999 to a maximum of 22.64% for maize in 1999, with an average value of 16.60%.

The isotropic semivariograms for yield showed the existence of a spatial structure (Fig. 2). The range varied from a minimum of 16.2 m to a maximum of 73.2 m for soybean and maize cultivated in 2002 and 1998, respectively, and the exponential model generally fitted the semivariance—except for maize in 2000, with an average range of 50 m and an average value of R^2 greater than 0.80 during the crop rotation. The nugget effect explained 30% of the semivariance on average, corresponding to a variance of 0.30 t ha^{-1}, except for maize in 2000 for which the noise was not detected. The level of variation for semivariance – sill values – was quite similar over years, ranging from a

Table 2
Descriptive statistics for field mean yield data measured during the crop rotation (1998–2002) and for stable area with high (HS) or low (LS) yield level

Statistics	Measured yield data (t ha^{-1})														
	Maize (1998)			Soybean (1999)			Maize (2000)			Wheat (2001)			Soybean (2002)		
	Field	HS	LS	Field	HS	LS	Field	HS	LS	Field	HS	LS	Field	HS	LS
Mean	11.21 a	10.92 aA	8.20 A	4.81 a	4.45 aA	4.17 bA	9.57 b	9.45 aB	6.91 bB	7.38	7.10 a	5.80 b	3.84 b	3.41 aB	2.68 bB
S.D.	2.54	0.77	1.39	0.60	0.20	0.16	1.97	1.01	0.79	1.15	0.42	0.57	0.45	0.26	0.20
CV (%)	19.9	14.24	15.55	12.4	4.36	3.86	20.5	10.62	10.95	15.58	5.87	9.50	11.7	7.57	5.96

Different lower-case letters (a and b) for the single year (the same crop) indicate statistically significant differences between HS and LS area, while different upper-case letters (A and B) refer to the statistically significant differences regarding the yield data registered for the same crop within HS or LS areas (LSD test, $P \leq 0.05$).

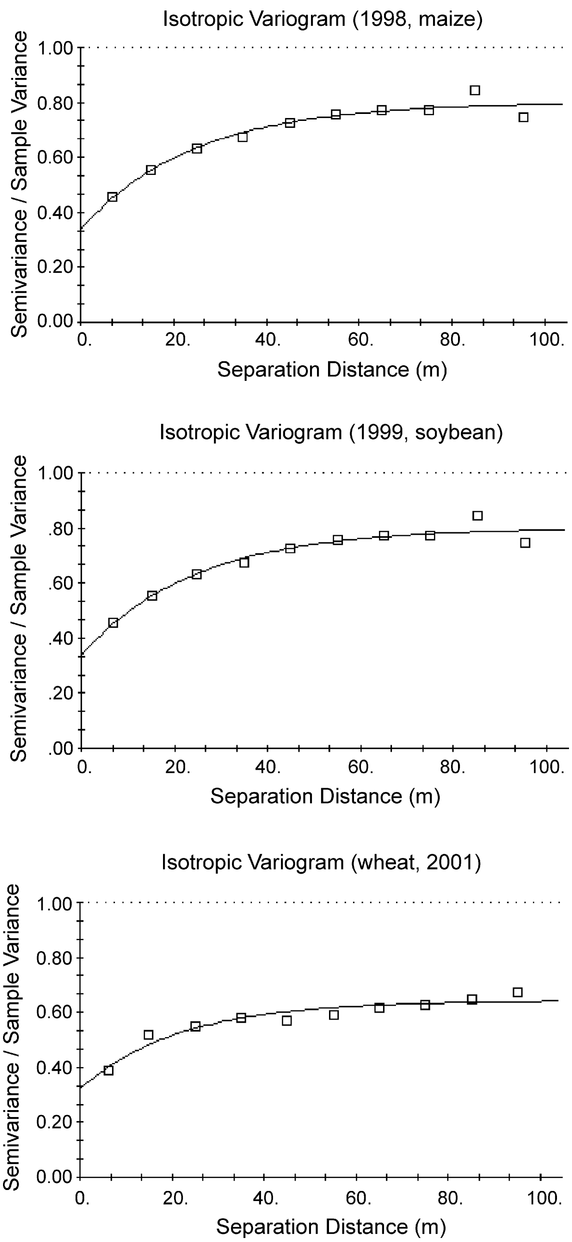

Fig. 2. Isotropic semivariograms of yield for each crop of the rotation.

minimum of 0.58 t ha^{-1} to a maximum of 0.80 t ha^{-1} for maize in 2000 and 1998, respectively, with an average semivariance of 0.71 t ha^{-1} over years.

The analysis of temporal stability, integrating the 5-year spatial pattern and temporal variance (Fig. 3) of yield, showed the presence of two stable zones, corresponding to approximately 50% of the field and having statistically higher or lower yield than the average value and lower temporal variance over years (Table 2). The results allowed for the identification of two distinct yield zones (north–south orientation), having a stable productive trend over years but different relative yield levels (Fig. 4). A small zone characterized by temporal instability (U zone) corresponded approximately to the boundary of the field and was not considered in the analysis. The small zone of unstable yield was located along the northern and southern boundary lines of the field, probably due to errors affecting yield mapping and greater soil compaction due to the traffic of machinery during tillage operations. The soil profile was different for the two stable zones. The HS zone was characterized by a deeper exploitable soil profile than the LS zone, because of the presence in the latter of greater soil strength in the deeper layer. The volume available for root growth was different, the greater volume corresponding to the HS zone (0–60 cm), compared to the LS zone (0–45 cm). During the growing season, stresses were more relevant for the LS zone because of the slower water infiltration. Consequently, initial conditions of soil water were also different.

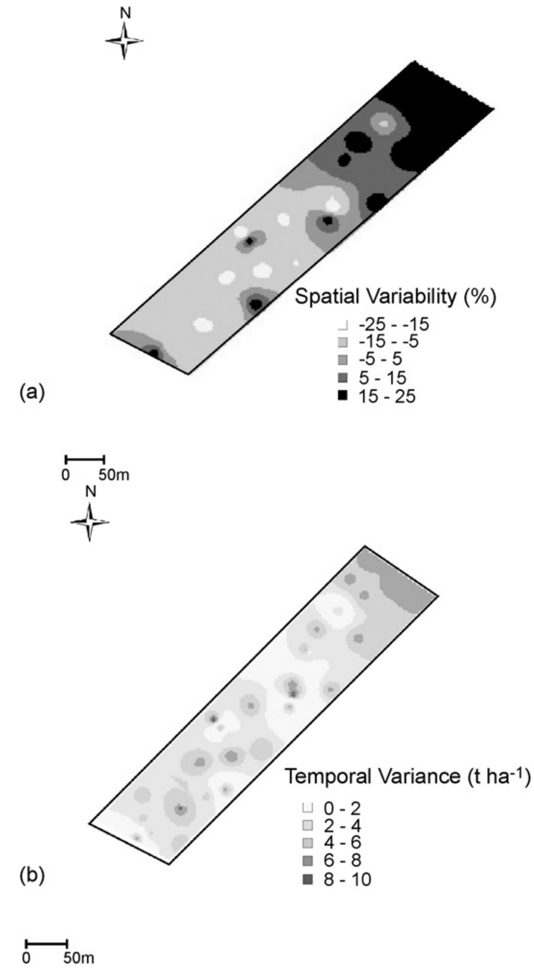

Fig. 3. Spatial pattern of yield over the 5-year crop rotation, expressed as average relative percentage difference from the average yield obtained within field (a); temporal variance (t ha^{-1}) revealed during the 5-year crop rotation within field (b).

3.2. Annual simulation and model evaluation

The model was used to simulate yield for analyzing the long-term temporal stability of yield spatial patterns. The model inputs were measured on site and site specific input were used on each management zone. The unstable zone identified according to the stability criteria was not simulated because of the small surface area, but these data were entered in the nearest HS or

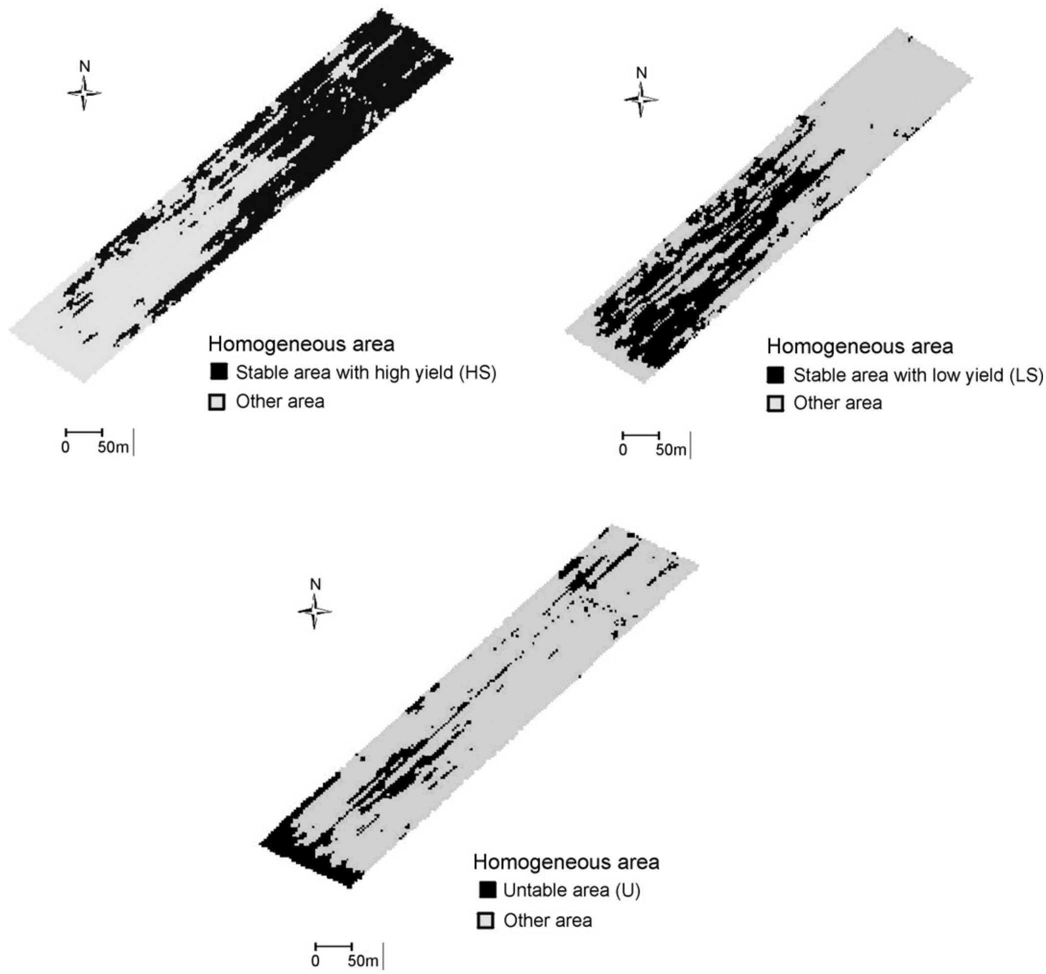

Fig. 4. Temporal stability map, reporting the presence of area within field having different stable level of production, identified as area having high yield (HS area) (upper left) and low yield (LS area) (upper right) pattern over years. The map in the bottom reports the within-field temporal instability of yield (U area).

LS zone. Differences were identified between growing seasons for the same crop and the LS and HS zones (Table 3). The overall comparison of measured and simulated yield data for the 2 zones and for the 35 points is shown in Fig. 5. The RMSE was rather low for all the crops, demonstrating the reliability of the model used. The same pattern was found for the comparison between simulated and measured yield data for the HS and LS zones. The difference between the simulated and the measured value of yield was statistically significant for maize only in 1998 within the complete field (Table 3). The simulated production was lower than measured, a result of the HS and the LS zones identified in the same growing season. Considering the stable zone (HS), the simulated data were greater than measured in LS zone in 2000. Despite the statistically significant differences described, the percentage difference for the two growing seasons was lower in both years than 12% (12% in 1998 and 2.6% in 2000, respectively). The difference between simulated and measured yield values for wheat was statistically significant because of the over-estimated yield data (Table 3), within both the complete field and the stable zone identified according to the level

Table 3
Simulated yield ($t\,ha^{-1}$) during the 5-year crop rotation for the whole field and the stable area with high (HS) or low (LS) yield level

Area	Simulated yield data ($t\,ha^{-1}$)														
	Maize (1998)			Maize (2000)			Soybean (1999)			Soybean (2002)			Wheat (2001)		
	Mean	S.D.	RMSE	Mean	S.D.	RMSE	Mean	S.D.	RMSE	Mean	S.D.	RMSE	Mean	S.D.	RSME
Field	8.96	0.58	2.11	8.59	2.79	1.95	3.12**	0.12	1.38	2.60	0.96	0.76	7.67*	0.57	0.95
HS	10.12	0.35	1.94	10.06*	1.81	1.74	3.18**	0.03	1.40	3.27	0.55	0.53	7.86*	0.51	1.10
LS	7.81	1.17	2.24	6.24	1.19	2.11	3.06**	0.40	1.37	2.05***	0.78	0.92	6.14*	0.88	0.80

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

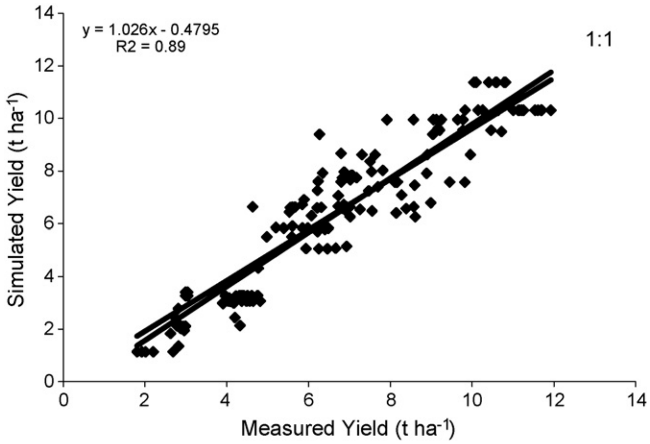

Fig. 5. Simulated vs. measured maize, wheat and soybean yield for 5 years and 35 points.

of yield obtained. However, the average percentage difference between the simulated and the measured yield data was appreciably lower (8%) than 12%, and the accuracy of the simulation was considered acceptable. The differences between simulated and measured yield values for the complete field for soybean were significant and negligible in 1999 and 2002, respectively (Table 3). In particular, the difference was statistically significant for 1999 in all the scenarios considered, both for the complete field and the identified stable zone, as confirmed by the percentage difference between the simulated and the measured yield data, being twofold greater than the threshold limit of 15%, and consequently by the RMSE. Despite that, in 2002, this difference was generally lower (12%) and appreciable only for the LS zone, being negligible for the HS zone. Based on the data obtained for the different annual scenarios, the performance of the prediction of yield data was acceptable, according to the values of RMSE.

3.3. Simulated long-term climate variability effects on spatial pattern of yield

The simulated long-term yield patterns showed statistically significant differences in yield data obtained in different years. Intra-year variability was observed for some growing seasons, with different patterns for different crops, and a similar pattern between HS and LS zones for different crops. For maize, the long-term simulated yield showed a variable response to climatic conditions, with higher yield for years having greater rainfall and lower average temperature values. The intra-year variability was also appreciable for some growing seasons, as revealed by the variable standard deviation of yield data with a maximum variability of $\pm 4.19\,\mathrm{t\,ha^{-1}}$ in 1992. In particular, the simulated yield was statistically different between the stable zone identified, except for the 1989 growing season, probably due to greater rainfall that occurred during the growing season. Fig. 6 shows a cumulative probability function of simulated yield for three crops for the 14 years simulation and for the two management zones. For maize, the yields were neither greater than $14\,\mathrm{t\,ha^{-1}}$ nor lower than $10\,\mathrm{t\,ha^{-1}}$ in the HS zone, while the LS zone showed a greater range of variation from 11 to $5\,\mathrm{t\,ha^{-1}}$. For wheat, the long-term simulated yield showed a variable response over the period considered, with an average value of $6.8\,\mathrm{t\,ha^{-1}}$ and values ranging from 10.5 to $5\,\mathrm{t\,ha^{-1}}$ in the HS zone and from 9 to $2\,\mathrm{t\,ha^{-1}}$ in the LS zone. The intra-year variability was considerable, particularly for some growing seasons, as revealed by the variable standard deviation of yield data and the coefficient of variation that varied from 0.26 to 67.34% in 1994 and 1999, respectively. For soybean, the long-term simulated yield showed a variable response for two zones with an average yield of $2.56\,\mathrm{t\,ha^{-1}}$. Yield values ranged from $3.21\,\mathrm{t\,ha^{-1}}$ in 2001 to $1.10\,\mathrm{t\,ha^{-1}}$ in 1994. The intra-year variability ranged from a minimum of 5.55% in 1995 to a maximum of 55.31% in 1994. With regard to the stable zones, the differences between HS and LS zones resulted in statistically significant differences over the long-term period. The yield simulated in the HS zone was generally statistically different from the one obtained in the LS zone, with the long-term average being slightly greater than $1\,\mathrm{t\,ha^{-1}}$. In particular, the differences detected were appreciable for the growing seasons having lowest rainfall, as, for example, in 1992 or the 1994. The cumulative probability function calculated for soybean showed a relatively close interval of variation of yield. Simulated yields ranged from slightly lower than $2.5\,\mathrm{t\,ha^{-1}}$ ($P = 30\%$) to about $3\,\mathrm{t\,ha^{-1}}$ ($P = 75–90\%$), with a probability of 50% to obtain an

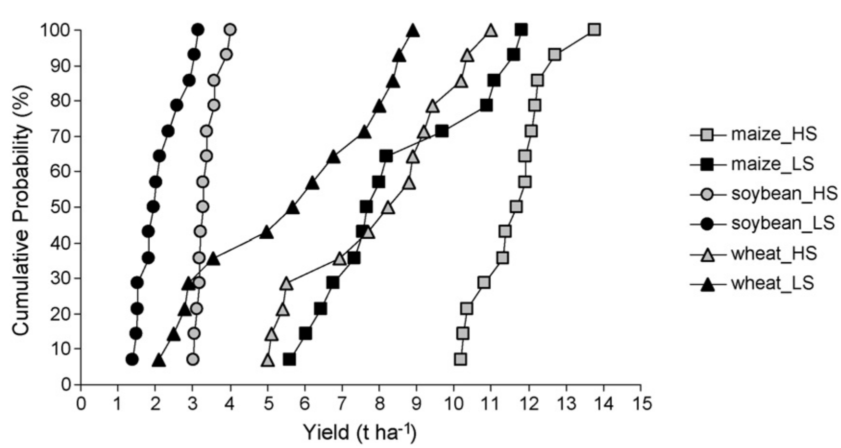

Fig. 6. Cumulative probability function for simulated yield of maize, soybean and wheat (1989–2002) for the two zones (HS and LS).

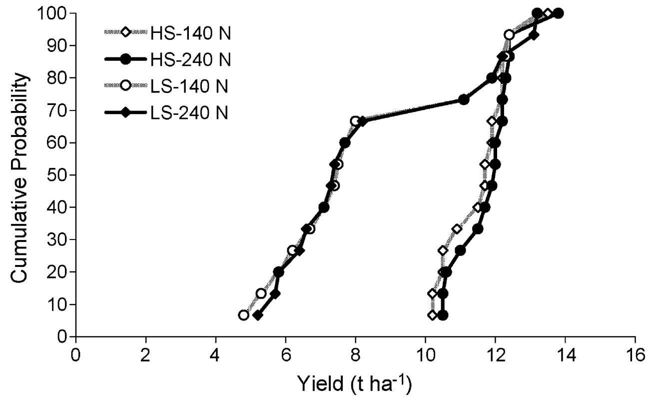

Fig. 7. Curative probability of yield for the HS and LS zones with 140 and 240 kg N ha^{-1} applied.

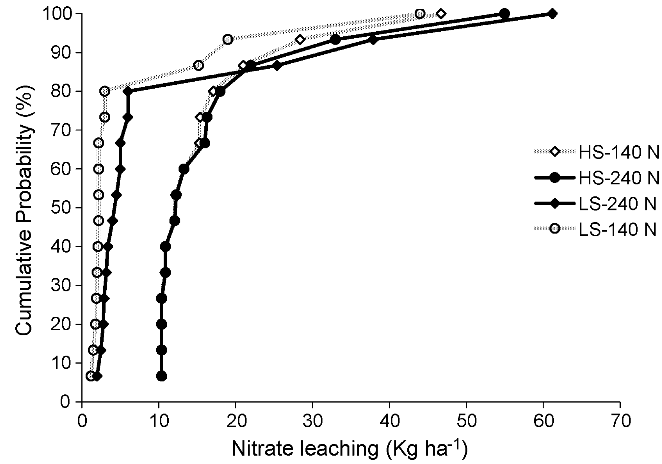

Fig. 8. Curative probability of nitrate leaching for the HS and LS zones with 140 and 240 kg N ha^{-1} applied.

average simulated yield value close to the value of 2.5 t ha^{-1} measured.

The long-term simulated yield was variable for all crops considered, confirming the statistically significant influence of climatic data on the average yield level, while for different stable zones identified. The difference was appreciable, because of the partial influence of different soil properties, in particular when climatic conditions were not favourable for crop growth.

3.4. *Estimating yield and environmental consequences of two N rates on the management zones*

One of the emerging issues driving the future of precision agriculture is environmental protection. The ability to manage the landscape in a variable way is a new tool that opens new opportunities in the area of environmental policy and protection. Variable rate management, such as variable nutrients (Miao et al., 2006), tillage (Basso et al., 2003), plant population (Paz et al., 2003), etc., offers the possibility of managing small units within a field to achieve optimum economic gross margins as well as environmental policy objectives. Process-oriented crop growth models can play an important role in quantifying the climate effect on yield and in linking environmental policy with producer economics (Thorp et al., 2006). This can be demonstrated with the following simulated experiment performed on the two management zones identified in the field. Considering the trade-off between nitrogen application rate with yield and nitrogen leaching, Fig. 7 shows a simulated yield response to 140 and 240 kg N ha^{-1} for the HS and LS zones over a 15 seasons. The N rates selected were chosen to represent a lower and higher amount of N fertilizer to a maize crop normally applied by the farmer of the study area. We decided to perform this exercise to show that once management zones have been identified, crop models can help find the best management zones that optimizes yield and environmental issues, such as nitrate leaching over space and time. The yield was rather different between zones but similar for the N rates applied, demonstrating that for this specific case, the N rate could have been reduced without reducing the yield. On the contrary, increasing N rate application for the LS zone would not guarantee an increase in yield for most of the years (70%) that the simulation was run. Fig. 8 shows the cumulative probability of nitrate leaching as functions of the two N rates applied. This relationship represents the environmental impact of different nitrogen management strategies. The higher N rate (240 kg ha^{-1}) produced higher nitrate leaching for both zones, but it was no significantly different from the (140 kg ha^{-1}). The main differences in leaching were again related to the zone, thus soil characteristics, etc., rather than the amount of N rate applied. The trend is consistent for 80% of the seasons, but in the remaining 20% of seasons, nitrate leaching was increased independently of zones and rates. The higher amount of leaching was observed in the 240 kg N ha^{-1} for the LS, demonstrating that the increase in N application in the LS zone would increase leaching without improving the yield as shown in Fig. 7. The analysis showed that 140 kg ha^{-1} would be the most environmentally safe rate of N to apply for both zones. The higher yield obtained with the 240 kg ha^{-1} in the HS may not justify the additional 100 kg N ha^{-1} applied both for the economic gross margins as well as the environmental impact. The two figures together can be used to link environmental policy and economic consequences to the producer. For instance, an environmental policy may state that 80% of the time the nitrogen loss from a field cannot exceed 30 kg ha^{-1}, the 240 kg N ha^{-1} could still be used, but may not increase the gross margins due to the lower rate of yield increase per unit of N applied. This directly links environmental policy to economic consequences and aids policy makers in determining how to provide incentives for environmental policies.

In conclusions, the combination of GIS tools and crop growth simulation models allowed for the identification of homogenous and stable zones within a field, according to the stability criteria. In particular, the simulation model was a useful tool to identify homogeneous zones, accounting for the temporal variability due to the influence of climatic conditions.

References

Basso, B., Ritchie, J.T., Pierce, F.J., Braga, R.P., Jones, J.W., 2001. Spatial validation of crop models for precision agriculture. Agric. Syst. 68, 97–112.

Basso, B., Cammarano, D., De Vita, P., 2004. Remotely sensed vegetation indices: theory and application for crop management. Riv. di Agrometeorologia 1, 34–54.

Basso, B., Sartori, L., Bertocco, M., Olivero, G., 2003. Evaluation of variable depth tillage: economic aspects and simulation of long term effects on soil organic matter and soil physical properties. In: Staffor, J., Werner, A. (Eds.), Precision Agriculture, pp. 62–70.

Batchelor, W.D., Basso, B., Paz, J.O., 2002. Examples of strategies to analyse spatial and temporal yield variability using crop models. Eur. J. Agron. 18, 141–158.

Bjarne, J., Steffen, H., 2003. Intra-field variations over crops and years. Eur. J. Agron. 19, 23–33.

Blackmore, S., Godwin, R.J., Fountas, S., 2003. The analysis of spatial and temporal trends in yield map data over six years. Biosyst. Eng. 84 (4), 455–466.

Blackmore, B.S., 2000. The interpretation of trends from multiple yield maps. Comp. Electron. Agric. 26, 37–51.

Booltink, H.W.G., van Alphen, B.J., Batchelor, W.D., Paz, J.O., Stoorvogel, J.J., Vargas, R., 2001. Tools for optimizing management of spatially-variable fields. Agric. Syst. 70, 445–476.

Boote, K.J., Jones, J.W., Hoogenboom, G., Pickering, N.B., 1998. The CROPGRO for grain legumes. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Boston, USA, pp. 99–128.

Brock, A., Brouder, S.M., Blumhoff, G., Hofmann, B.S., 2005. Defining yield-based management zones for corn–soybean rotations. Agron. J. 97, 1115–1128.

Cassel, D.K., Wendroth, O., Nielsen, D.R., 2000. Assessing spatial variability in an agricultural experiment station field: opportunities arising from spatial dependence. Agron. J. 92, 706–714.

Chang, J., Clay, D.E., Carlson, C.G., Reese, C.L., Clay, S.A., Ellsbury, M.M., 2004. Defining yield goals and management zones to minimize yield and nitrogen and phosphorus fertilizer recommendation errors. Agron. J. 96, 825–831.

Cora, J.E., Pierce, F.J., Basso, B., Ritchie, J.T., 1999. Simulation of within-field variability of corn yield with CERES-Maize model. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), Proceedings of the 4th International Conference on Precision Agriculture. Minneapolis, MN, USA, 19–22 July 1998. ASA, CSSA and SSSA, Madison, WI, USA, pp. 1309–1319.

Doerge, T.A., Gardner, D.L., 1999. On-farm testing using the adjacent strip comparison method. In: Robert, P.C., et al. (Eds.), Precision Agriculture: Proceedings of the 4th International Conference. St. Paul, MN, 19–22 July 1998. ASA, CSSA, and SSSA, Madison, WI, pp. 603–609.

Ferguson, R.B., Lark, R.M., Slater, G.P., 2004. Approaches to management zone definition for use of nitrification inhibitors. Soil Sci. Soc. Am. J. 67, 937–947.

Fleming, K.L., Westfall, D.G., Wiens, D.W., Brodahl, M.C., 2001. Evaluating farmer defined management zones for variable rate fertilizer application. Precision Agric. 2, 201–215.

Fraisse, C.W., Sudduth, K.A., Kitchen, N.R., 2001. Calibration of the CERES-Maize model for simulating site-specific crop development and yield on claypan soils. Appl. Eng. Agric. 17, 547–556.

Franzen, D.W., Hopkins, D.H., Sweeney, M.D., Ulmer, M.K., Halvorson, A.D., 2002. Evaluation of soil survey scale for zone development of site specific nitrogen management. Agron. J. 94, 381–389.

Fridgen, J.J., Kitchen, N.R., Sudduth, K.A., Drummond, S.T., Wiebold, W.J., Fraisse, C.W., 2004. Management Zone Analyst (MZA): software for subfield management zone delineation. Agron. J. 96, 100–108.

Gamma Design Software, 1999. GS+: Geostatistics for the Environmental Sciences, v.3.5. Gamma Design Software, Plainwell, MI, USA, p. 44.

Hoogenboom, G.J., Jones, J.W., Wilkens, P.W., Batchelor, W.D., Bowen, W.T., Huntal, L.A., Pickering, N., Singh, U., Godwin, D.C., Baer, B., Boote, K.J., Ritchie, J.T., White, J.W., 1994. Crop models. In: Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), DSSAT v.3, vol. 2-2. University of Hawaii, Honolulu, Hawaii.

Inman, D., Khosla, R., Westfall, D.G., Reich, R., 2005. Nitrogen uptake across site specific management zones in irrigated corn production systems. Agron. J. 97, 169–176.

Joernsgaard, B., Halmoe, S., 2003. Intra-field yield variation over crops and years. Eur. J. Agron. 19, 23–33.

Jones, C.A., Kiniry, J.R., 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. Texas A&M University Press, College Station, TX, USA, p. 194.

Machado, S., Bynum, E.D., Archer, T.L., Bordovsky, J., Rosenow, D.T., Peeterson, C., Bronson, K., Nesmith, D.M., Lascano, R.J., Wilson, L.T., Segarra, E., 2002. Spatial and temporal variability of sorghum grain yield: influence of soil, water, pests and diseases relationships. Precision Agric. 3, 389–406.

McBratney, A., Whelan, B., Ancev, T., 2005. Future directions of precision agriculture. Precision Agric. 6, 7–23.

Miao, Y., Mulla, D.J., Batchelor, W.D., Paz, J.O., Robert, P.C., Wiebers, M., 2006. Evaluating management zone optimal nitrogen rates with a crop growth model. Agron. J. 98, 545–553.

Mulla, D.J., 1991. Using geostatistics and GIS to manage spatial patterns in soil fertility. In: Kranzler, G. (Ed.), Proceedings of the Automated Agricultural for the 21st Century. Chicago, IL, 16–17 December 1991. ASAE, St. Joseph, MI.

Paz, J.O., Batchelor, W.D., Babcock, B.A., Colvin, T.S., Logsdon, S.D., Kaspar, T.C., Karlen, D.L., 1999. Model-based technique to determine variable rate nitrogen for corn. Agric. Syst. 61, 69–75.

Paz, J.O., Batchelor, W.D., Jones, J.W., 2003. Estimating potential economic return for variable soybean variety management. Trans. ASAE 46, 1225–1233.

Pierce, F.J., Nowak, P., 1999. Aspects of precision agriculture. Adv. Agron. 67, 1–85.

Pringle, M.J., McBratney, A.B., Whelan, B.M., Taylor, J.A., 2003. A preliminary approach to assessing the opportunity for site-specific crop management in a field, using yield monitor data. Agric. Syst. 76, 273–292.

Ostergaard, H.G.S., 1997. Agronomic consequences of variable N fertilization. In: Stafford, J.V. (Ed.), Proceedings of the 1st European Conference on Precision Agriculture. BIOS Scientific Publishers, Oxford, United Kingdom, pp. 315–320.

Ritchie, J.T., Gerakis, A., Suleiman, A., 1999. Simple model to estimate field-measured soil water limits. Trans. ASAE 42, 1609–1614.

Ritchie, J.T., Otter, S., 1985. Description and performance of CERES-Wheat: a user-oriented wheat yield model. In: ARS Wheat Yield Project. ARS-38. Natl. Tech. Info. Serv., Springfield, MO, USA, pp. 159–175.

Robert, P.C., 1993. Characterisation of soil conditions at the field level for soil specific management. Geoderma 60, 57–92.

Robert, P.C., 2002. Precision agriculture: a challenge for crop nutrition management. Plant Soil 247, 143–149.

SAS Institute Inc., 1999. The SAS System for Windows Version 8.0. SAS Institute Inc., Cary, NC, USA.

Schepers, A.R., Shanahan, J.F., Liebig, M.A., Schepers, J.S., Johnson, S.H., Luchiari Jr., A., 2004. Appropriateness of management zones for characterizing spatial variability of soil properties and irrigated corn yields across years. Agron. J. 96, 195–203.

Thorp, K.R., Batchelor, W.D., Paz, J.O., Steward, B.L., Caragea, P.C., 2006. Methodology to link production and environmental risks of precision nitrogen management strategies in corn. Agric. Syst. 89, 272–298.