Opportunities and limitations for the application of simulation and modeling as a support for precision farming

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ABSTRACT. Precision farming has been suggested for the strategic management of agricultural crops on a smaller scale than total farm area, based on the use of information technology and agronomic know-how. In order to be successful in this activity, it is necessary to be able to manage the variation of plant and soil variables; this requires that data be collected and analyzed for decision-making process. The modeling of interactions between soil, weather and crop growth would be a natural choice for the integration and search for management strategies. However, further study of modeling for precision farming is needed, with regard to soil-structure and integrated-plant properties. An experiment was conducted in Angatuba, São Paulo, Brazil (23º33'S; 48º18'W; 670m), in which a maize crop was observed during two growing seasons (1999-2000) in two different areas where yield-related properties of soil and plant variables were monitored. Specific-site analyses were carried out in one area, using a simulation model based on a single sampling of soil properties. In the other area, the implementation potential of this new technology - with modeling and simulation as supporting tools - was discussed, based on the spatial structure of plant and soil variables, obtained in intensive sampling. Results from field observations suggest that modeling of biophysical processes is a fundamental tool for the implementation of precision farming, based on a realistic work scale and using sampling strategies from multiple sources, which should include remote sensing imagery. In the present case, grid soil sampling on a field scale was shown to be inconsistent with precision-farming needs, in terms of the extension of the application of modeling based on point processes, to the space of an area.

Key words: maize, modeling, precision farming.

RESUMO. Oportunidades e limitações para aplicação de simulação e modelagem como suporte à agricultura de precisão. A agricultura de precisão tem sido proposta como manejo estratégico de cultivos agrícolas, em escala menor do que a área total da lavoura, com base na aplicação de informação tecnológica e conhecimento agronômico. O gerenciamento da variação de variáveis de solo e planta se faz necessário para se obter sucesso nesta atividade. Tal fato implica em se lidar com grande número de dados, que devem ser coletados e tratados visando ao desenvolvimento do poder de decisão. A modelagem das interações do complexo solo-clima-desenvolvimento de culturas tende a ser uma escolha natural para a rápida integração e busca por estratégias de manejo. Um experimento foi desenvolvido em Angatuba, Estado de São Paulo (23º33'S; 48º18'W; 670 m), e a cultura do milho foi observada através de duas de estações de crescimento (1999-2000), em duas áreas de cultivo distintas. Foi efetuado o monitoramento de propriedades de solo, relacionadas à produtividade agrícola, além de variáveis de planta. Para uma das áreas análises sítio-específico, foram conduzidas através do uso de modelo de simulação, com base em amostragem esparsa de propriedades de solo. Em uma segunda área, o potencial de implementação desta nova tecnologia, tendo a modelagem e simulação como suporte, foi discutido, com base na estrutura espacial de variáveis de planta e solo, obtidas em amostragem intensiva. Os resultados das observações de campo sugerem que a modelagem de processos físicos é uma ferramenta fundamental para a implementação da agricultura de precisão, tendo por base uma escala de trabalho realística e a utilização de estratégias de amostragem a partir de fontes múltiplas, que devem incluir o sensoriamento remoto. No presente estudo, a malha de amostragem de solo, em uma escala de lavoura, mostrou-se inconsistente com as necessidades da agricultura de precisão, no que se refere à extensão da aplicação de modelagem, baseada em processos pontuais, para o espaço de um área.

Palavras-chave: milho, modelagem, agricultura de precisão.

Precision farming involves the use of high-resolution spatial plant and soil data, among other information, to put decision-making on a smaller, i.e. more detailed scale, based on the use of information technology. Using satellite-positioning and electronics-communication standards, position and time may now be integrated into all procedures related to farming.

For many years agriculturists have been striving to understand and improve crop-management techniques on a field-by-field basis. Comprehensive guidance is now available for major crops in order to apply important management options on an "within-field" basis.

In fact, most physical, chemical and biological properties of soil in an agro-ecosystem are variable in space, even when short distances are considered (Santos *et al.,* 2001a). However, field implementation of the agronomic practices and treatments are done uniformly over a wide range of conditions, where the variability of a large number of yield-related properties are expressed. This creates a contradictory notion about the agronomic know-how; at the same time it raises attractive expectations about managing the discussed variability for the farmers' benefits.

Precision farming has arisen mainly in response to advances in technology, rather than through developments in the fundamental sciences which support agriculture. Traditionally, it was linked to variable-rate application of material inputs such as fertilizers and pesticides. Although a small number of practical results, in terms of economical feasibility, were published, most of the citations refer to other inputs, such as time and labor (Sparovek and Schnug, 2001). Another controversial notion about precision farming is the economic-based analysis against the environmental advantages of its adoption, mainly with regard to reducing air pollution and ground-water contamination (Plant, 2001).

For the field-scale implementation, precision-farming strategies have a "specific case" basis; therefore, analysis for a large number of situations and climatic conditions is required for the development of critical pressure on the issue.

It has been suggested that, by accumulating crop-yield maps over several years, a consistent pattern emerges, which may be used either directly in adjusting inputs, or to delineate zones for further investigation. Collecting soil data in a defined grid could also improve delineation and management of the discussed zones, since a certain level and structure of variability of soil properties would be expected for a specific area. However, a more accurate discussion is needed to clarify aspects of data collection, analysis and integration for precision-farming strategies, which could assist the discussion and raise subsidies for any analysis concerning the potential and limitations for its implementation.

The working-scale of this new technology will perhaps be governed by the feasibility of sampling for environment description. Costs of this activity will bring simulation and modeling as a natural choice, as a standard for management and scientific investigation.

The integration of a large amount of data, and the use of that data to extract useful information for guidance and prescription, is one of the main problems affecting precision farming. The crop modeling approach makes possible the more rapid integration of a collection of data concerning soil, plant and climate, to explore variability and assist decision-making. However, modeling crop growth and its environmental interactions is traditionally linked to single-point estimation; thus, further investigation will be needed for scaling up physically-based process simulation to account for a multiple source of variability, in the space of a single area. This is an important point to consider when searching for modeling capability to support precision farming, moreover for GIS-based models in which continuous surface of interpolated soil and plant variables are required as information layers.

The aim of this work is to monitor and analyze some influential variables that are important for precision-farming implementation and to discuss some opportunities and limitations of crop-model use, as a support for decision-making, based on different soil sampling schemes carried out in two distinctive areas cultivated with corn.

Material and methods

Place, time and crop

The experiment was carried out during 1999-2000, at a private farm in Angatuba (SP), south-eastern state of São Paulo State, Brazil (23°33'S; 48°18'W; 670m). Two experimental areas were used for a specific-site analysis of some corn yield-related properties. The first was a 33.4 ha. area of irrigated corn. The second was a 40 ha. rain-fed cornfield. Both areas have smooth, sloping terrain.

The producers planted the crop in two consecutive growing seasons, around mid-September, in accordance with the official-research recommendation for the region, for high yield achievement, and concerning the two systems of water recharge of the soil.

Yield monitoring

Yield mapping was done for the rain-fed cornfield for the two growing seasons. Specific-site mapping of yield-data results was undertaken over an intensive grid of 40 000 observation points. Configuration for sensors and procedures for calibration, data collection and treatment were described by Santos *et al.* (2000a) and Santos *et al.* (2001b).

In the first growing season, plant-row direction was performed from north to south in the area. In the second year of observation, the row direction was changed and the opposite (normal) direction adopted.

Soil sampling and spatial analysis

Soil sampling for soil-particle distribution and soil-fertility analysis were taken in both areas. A 100m regular square grid was established for the irrigated field. A regular grid of 50 m was established for the rain-fed cornfield, and soil properties were analyzed for soil depths of 0-20 cm and 20-40 cm (Figure 7).

Based on grid configuration, soil samples were analyzed for clay, silt, sand, organic carbon contents, and water-retention.

Modeling the spatial distribution of soil properties was done using the standard estimation of semivariogram (Matheron, 1963):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N} \left[Z(x_i) - Z(x_i + h) \right]^2 \qquad (1)$$

where γ is the semivariance, N(h) is the number of the "paired" values Z(xi), Z(xi+h) separated at a certain distance by the vector h.

The spatial features of data in all cases were performed with the prior removal of possible linear trend. So equation (1) was always applied to residues instead of to original data, according to the procedure described by Valeriano (1999).

The soil of the irrigated area was classified according to Prado (1991) and Embrapa (1999). Three soil units were delineated in the area,, namely LVd-2 (Latossolo Vermelho distrófico típico, textura argilosa, A moderado), LVd-1 (typical dystrophic red latisol, clayey texture, A moderate) and LVAd (yellow-red latisol, typical dystrophic, extremely clayey texture, A moderate) (Figure 1). According to North American classification, these soil units are described as Rhodic Hapludox and Typic Hapludox (Soil Survey Staff, 1996).

Modeling of soil, plant and climate variables

Integrated modeling of soil, plant and climate variables was used to explore some aspects related to "within-field" variation in the irrigated area, using the Ceres-Maize model, attached to DSSAT3.5 interface (Jones and Kiniry 1986) (IBSNAT 1990). Ceres-Maize model performs a daily step simulation of crop growth and development, based upon carbon, nitrogen and water balance (Thornton and MacRobert, 1994; Jones and Kiniry, 1986). It requires soil, plant and climatic data: soil data were obtained from the soil-sampling scheme in the areas, plant data are related to management data and genetic plant coefficient (IBSNAT 1990), which were obtained from observation of the growth and development of corn in the areas during analysis. Tillage practices were differentiated for LVd-1 unit, which comprises almost half of the south-eastern portion of the area. Only in this case was the winter cover crop (barley) removed for hay in the two growing seasons. Therefore, the estimated initial conditions (nitrogen, crop residue) were treated accordingly in this soil unit, when building up the Ceres-Maize data-base (IBSNAT 1990).

Climatic data was obtained from an automatic meteorological station installed close to the experiment. Climatic data for a medium-term (ten years of data) modeling analysis were obtained either from a pluviometric collecting point near to the experiment, or from a meteorological station located 30 km from the experiment site.

Results and discussion

Modeling processes in the "management unit" scale

Figure 1 shows a 34.3 ha. irrigated cornfield, separated into three types of soil. Results from soil classification show variation of soil type in the area, which might demonstrate a good opportunity for precision-farming strategies. However, soil type is not directly related to final yield, and building up management units could require a larger number of data analyses. However, based on point-soil sampling for soil-water retention data, the modeling of the water balance was done by the Ceres-Maize model into Dssat interface.

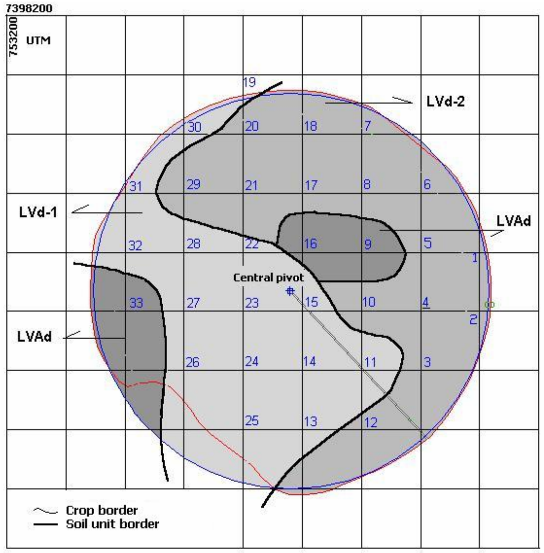

Figure 1. Irrigated cornfield with soil classification in south-eastern São Paulo State, (Brazil); sampled sites and classified soil units LVd-1, LVd-2 and LVAd are shown

Results showed that, based on contrasts of soil properties, related to soil-water retention and also due to differences in the management pattern, a different notion of potential extractable water can be seen for the three soils in the irrigated area (Figure 2). A different pattern for water availability may be envisaged in this area, based on this data modeling, which could influence distribution of final yield in the separate areas. Since nitrogen leaching is dependent upon water balance, a different potential for ground-water contamination may also be envisaged in this area in the case of excessive use of fertilizers. The same conclusion is also possible with respect to the movement of pesticides.

Figure 1 shows "in-area" differences in the water-estimate elements. However, the simulation of yield, separately for all the soil units, and for a single growing season analysis, would depend on a model improvement, or rather, a gain in sensitivity to crop changes in growth and development, which is not being achieved currently.

A better exploration of modeling, applied to the three separated soils (Figure 1), may be done by further analyzing the final-yield simulation according to the seasons, in order to see the time-space interaction between soil, weather and crop growth in a varied base of water balance and different pattern of the daily step incidence of meteorological variables.

Figure 3 shows the results from the Ceres-Maize simulation of final yield for ten consecutive years, while testing six nitrogen application rates for the more contrasting soils, in terms of applied management and soil sampled properties for soil-water.

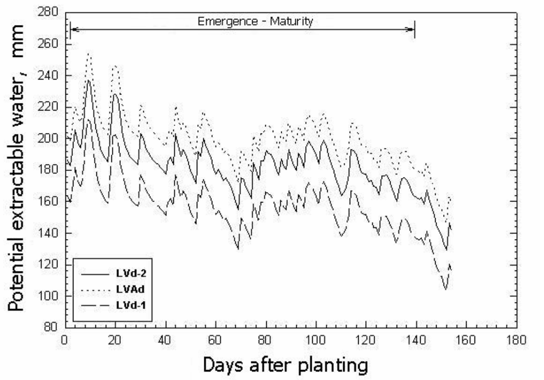

Figure 2. Simulated potential extractable water for three different types of soil explored in an irrigated cornfield in the south-eastern state of São Paulo, Brazil.

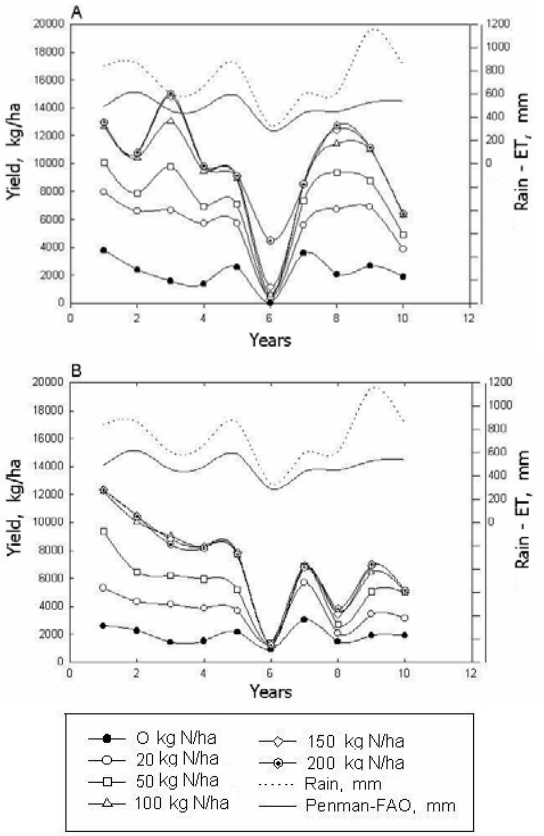

Figure 3. Simulated final yield along 10 years of climatic data and testing 6 nitrogen application rate, in an irrigated cornfield, in the south-eastern state of São Paulo, Brazil; (a) is LVd-2 and (b) is LVd-1 soil unit

Figure 3 clearly shows that in the beginning, for all nitrogen levels, the two contrasting soils did not differentiate themselves. However, as time goes by, the LVd-1 presents the worse performance for all nitrogen levels. The highest level of nitrogen giving response was around 100 kg/ha, suggesting this level to be the maximum response for nitrogen-rate application. This demonstrates that the simulation results are realistic, since this is similar to the level of maximum nitrogen used in the area for average expected productivity of around 12 t/ha. Fluctuations in productivity over the years, for all nitrogen levels, reveal one important characteristic about this variable: the instability when tackling the daily step incidence of water regime and meteorological variables, such as rain, solar radiation and air temperature. This is particular important since we are concerned with two distinct spaces in the same area showing different patterns of fluctuation. It is also in accordance with the time-instability description of crop yield, which may be depicted from Jones (1991) and Kramer and Boyer (1995), among others.

Scaling up from point sampling to field maps

Despite the use of modeling of integrated variables from soil-plant-air continuum to explore management and decision-making purposes, as shown in Figures 2 and 3, a more challenging aspect of modeling should be considered, if one wishes to advance from a few-point sampling for a representative area (Figure 1) to a continuous-surface mapping of soil and plant properties. Soil information for any model such as the Ceres family or any other, would be achievable from grid sampling and using Geostatistics or other conventional methods, for building up surface information. In this case, linking the simulation processes to a GIS (Geographic Information System) have been discussed elsewhere (Ambuel *et al.,* 1994; Crosetto *et al.,* 2000).

Figures 4a and 4b show two surface-yield pieces of information obtained by intensive yield sampling, which might help in the discussion on the construction of continuous layers of information on important variables, such as water distribution. It might also help to prospect about modeling growth and related aspects. Figure 4 shows a pattern of variability in spatial final yield that is different between growing seasons. For the first season an ellipsoidal coalescent trend on yield data may be seen along the row direction. There is also a continued trend when the row direction was changed in the following growing season.

Despite the fertilization, which has an in-line distribution along the field, the coalescent profile trend, seen in the yield distribution along the row direction, suggests that the superficial and sub-superficial water infiltration and redistribution could be the main cause of that trend, which persisted during both growing seasons. Several studies have shown the level of importance of water storage and redistribution in a cultivated field (Hillel, 1998; Santos *et al.,* 2000a).

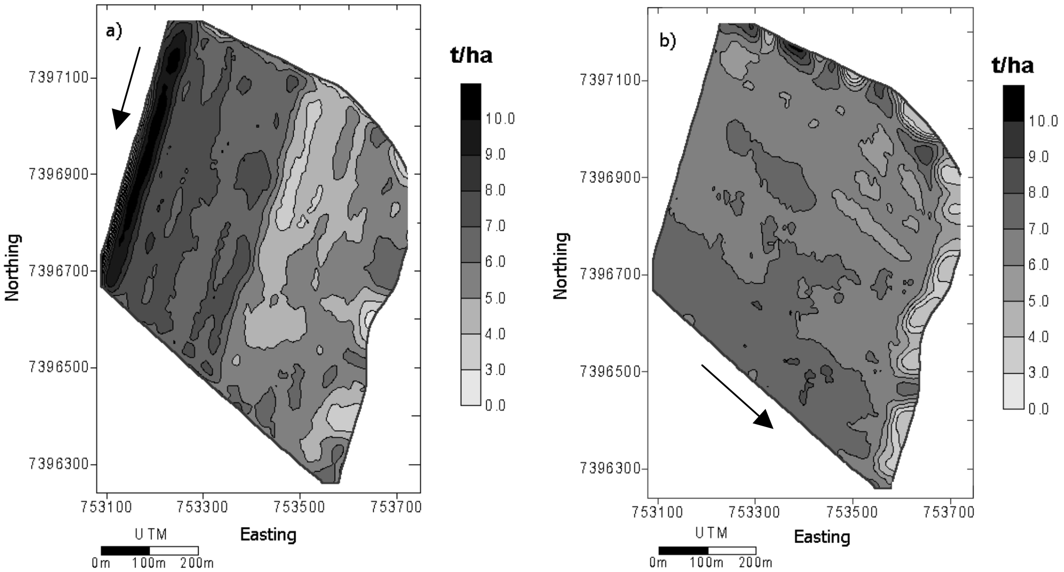

Figure 4. Corn-yield mapping for two different seasons [1999 (a); 2000 (b)] and two plant row directions, for the same area (40 ha), in south-eastern state of São Paulo, Brazil; arrows indicate plant-row direction

If a square grid were imagined inside the area (Figure 4), and general soil water budget, which is part of most crop-growth models, was applied, then we could have written for any "point-grid", for a given time interval (Cunha 1992):

$$\Delta A = P + I \pm R \pm D - ET \quad (1)$$

where A is the water storage, P is the rain, I is the irrigation depth, R is the Run-on or Run-off, D is drainage or capillary ascent of water and ET is the evapo-transpiration. Some terms in the equation (1) assume vital importance when moving from "point" estimation of crop development and yield to a "in-area" exploration, when considering the integrated soil-water parameters in the modeling. The R term is one of the parameters that must be reconsidered to account for a more realistic value for water dynamics along the field, mainly for building up continuous mapping and linking to GIS analysis.

The pattern of yield distribution seen in Figure 4 suggests a differential distribution of water-holding capacity along the field. This aspect, implicit in Equation (1), was explored for very small areas elsewhere (Timlin *et al.,* 2001). Modeling this parameter for a field scale might be difficult if the expected results are based only on soil-point sampling. Methods that allow data collecting in bulk, such as remote sensing, particularly air-borne videography, could fulfill this need, when modeling this particular aspect of soil-water.

Prospect about modeling special traits related to precision farming

Time-space yield variability, as suggested in Figure 3, brings another topic under discussion, linked to spatial water availability along the seasons, which could be further analyzed with the framework of precision-farming. It is related to plant-row structure and may be better worked out from the discussed yield-distribution pattern described in Figure 4.

Reduced equidistant plant spacing may be considered, and enquiries made about matching water-hold capacity distribution and seed rate for delineated contrasting areas for this particular input. This is based on the known impact of water storage and distribution on final yield.

In fact, this subject, overviewed in Figure 5, must include aspects of plant architecture, and its ability to convert photosynthetically-active radiation into carbohydrates, along the standard of competition between plants for water and nutrients. Modeling these aspects could lead to subsidies for implementing differential seeding rates. An investigation on modeling plant spacing, considering the above subject, would contribute to an improvement in precision farming.

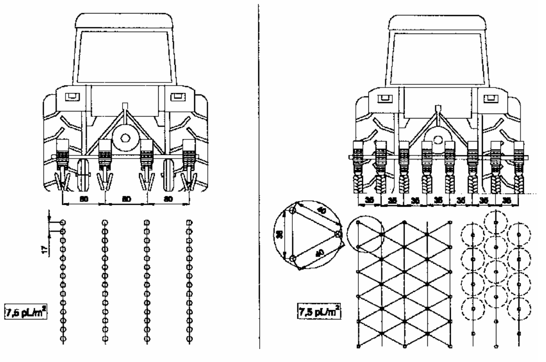

Figure 5. Diagram about prospecting investigation on equidistant seed rating for differential plant spacing, for a precision-farming environment; units are in cm. Adapted from Auernhammer (2001)

Field scale soil and plant variability as a modeling data source

Figure 6 shows the overall structure of spatial yield distribution along the rain-fed corn field, in the 2000/2001 growing season. The fitted variogram represented two orientations in the imaginary trigonometric circle for the area. Row direction and the normal to row-planting direction were considered. A distance of 96 m was determined as the range for maximum spatial correlation. Comparison of the maximum semivariance, for both directions analyzed, reveals anisotropy for yield-data distribution along the field.

The high value for the nugget effect (Isaaks and Srivastava, 1989) demonstrates that yield has a large randomness component for small distances, and also reveals a low level of spatial correlation, mainly for the direction of 22 degrees. Despite the level of yield-mapping uncertainty, suggested for the participation of the nugget effect in the total semivariance (Figure 5) in this case, the total number of sampled points (40 000) diminishes interpolation bias when building up continuous surface of yield information.

Figure 7 shows an intensive grid-sampling design for the area described in Figure 4, and also the spatial structure of easily-measured soil properties. These properties (e.g. clay, sand, silt) are important items for interpolated continuous surface in soil-physical description, and should be part of the management units' delineation. They are therefore important for GIS-based modeling of soil and plant behavior.

In Figure 7, the semivariograms were scaled to maximum semivariance. Therefore Y-axis has a maximum value of 1, which aids comparison of the nugget effect between variables (Valeriano, 1999). All soil properties have a considerable nugget effect, which means a large value for semivariance at zero distance. This is more clearly seen for coarse and medium sand. For these properties the nugget effect comprises the total value of semivariance.

The curve shapes prove a low level of spatial correlation for all soil properties. As a result, there appears to be a certain level of uncertainty when mapping continuous surfaces. In this case, kriging procedures become more like a simple averaging of the available data (Oliver and Webster 1990). This is of significant importance when linking modeling and GIS analysis, due to the lack of precision when estimating properties in unsampled locations, even for this very short field-scale grid spacing.

This kind of spatial structure shows a certain level of inconsistency for meeting precision-farming needs and makes it clear that, even for a very short sampling distance (Figure 7), as here, the construction of continuous soil-surface information, to supply source data for modeling purposes, would be difficult. This fact, in tandem with low values of CV (coefficient of variation), observed for most properties analyzed in the area (Santos *et al*., 2000b), suggests that, in this particular case, soil properties show an unfavorable spatial structure for easy variability management, namely, low CV values and low spatial correlation.

This shows that, in some cases at least, collecting data for precision-farming implementation, and therefore for building up a database for modeling the yield-related process, will include remote-sensing data in order to achieve the capability of managing variability.

In fact, crop plants integrate the effects of micro-climatic environment, stress (water, nutrient and disease) and soil properties. These effects are often expressed in a developed canopy. Therefore, measurements of soil and crop properties at sample sites, combined with multi-spectral imagery, could produce accurate and timely maps of soil and crop characteristics, for defining management units (Moran *et al.,* 1997). Gathering basic parameters to support crop modeling, such as leaf area index, leaf water potential and absorbed photosynthetically-active radiation, among others, was also experimentally demonstrated (Pinter, 1993). Provided these data are available, modeling crop-yield-related process could be better worked out to support specific-site prescription, even for larger areas.

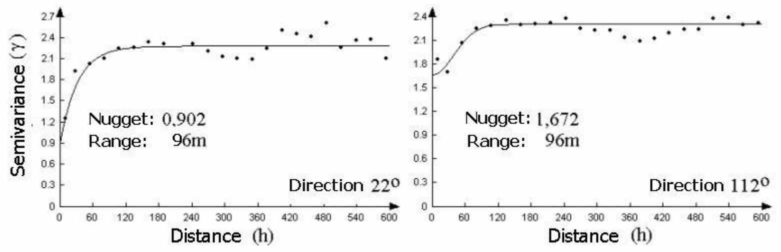

Figure 6. Variogram analysis for overall spatial yield distribution for two directions, in the 2000/2001 growing season of corn

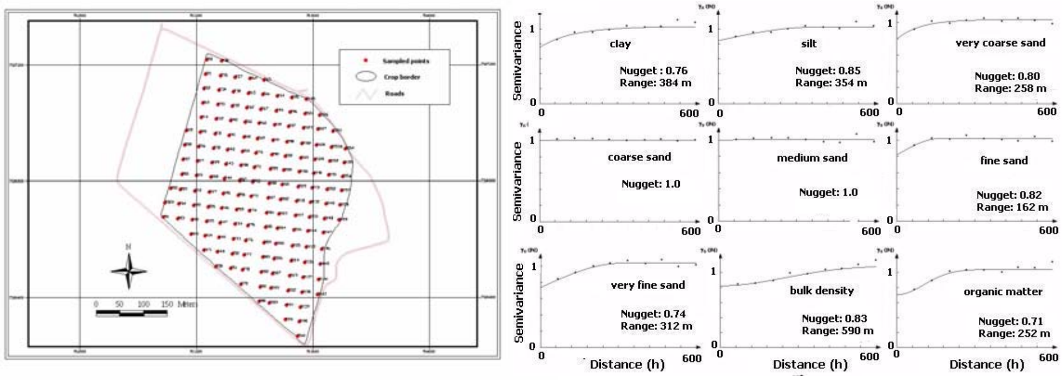

Figure 7. Sampling grid of regular spacing of 50m and variability structure for properties (clay, silt, sand, organic matter and bulk density), analyzed in the cornfield of 40 ha, in south-eastern state of São Paulo, Brazil. Y-axis are normalized residues. Results are for a soil depth of 0-20 cm

If a short working scale for the modeling area is taken into account, it seems clear that most available crop-modeling approaches do not contain structures that account for the most important features that could support full specific-site management in agricultural fields, due to the lack of suitable agronomic know-how. However, if a more realistic working scale is on the agenda, coupled to remote sensing, especially videography-based data, they might assist soil-crop modeling as source data. Consequently, supporting knowledge for specific-site management, based on the collection of soil, weather and crop data over several years, would be achieved faster.

Simulation algorithms applied to a "within-field" basis were sensitive to timely changes of soil, crop-growth and climate interactions

Extending the modeling of crop growth and yield from a point-process to an area-basis depends on understanding the crop-related process in a realistic working-scale and integrated environmental sampling scheme. The detection of canopy-expressed environmental interactions would probably allow modeling to support precision farming in larger areas.

As from the above results, field-scale observed soil properties, in a small square grid spacing, showed an inconsistency to support accurate precision-farming strategies, based on the need for the building up of continuous interpolated information layers.

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