INTEGRATING SPATIAL SOIL ORGANIZATION DATA WITH A REGIONAL AGRICULTURAL MANAGEMENT SIMULATION MODEL: A CASE STUDY IN NORTHERN TUNISIA

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Abstract. Cropping system simulation models are typically used to simulate crop growth and development at the field scale. Spatial extension of the results to larger scales needs spatially-referenced databases using Geographic Information System (GIS). However, GISs generally lack accuracy and pertinence in soil characteristics and soil delineations that are required for this purpose. In addition, most soil parameters used in the soil water models are empirical and are estimated without any reference to soil structure; making difficult to characterize the hydro-structural functionality of spatial soil mapping units in the GIS. The objective of this paper is to present an application of a new approach in soil physics for coupling soil information (mapping and characterization) system based on the soil organization with an agronomic model, CropSyst, to be used for soil and water management purposes. Accordingly, a GIS based on the map of hierarchical natural units in the irrigated area of Cebalat (Northern Tunisia) was used in order to build a geo-referenced soil information system for the study area. Additional information from the existing GIS of the zone was overlaid to produce "agronomic units" which results from the spatial superposition of the soil information system and the farm map units and land use. The inputs for the model were different sets of soil, crop and crop management parameters. Simulations were conducted at the field scale for testing the ability of CropSyst to simulate yield, soil water dynamics, soil salinity and nitrogen leached, and, at the regional level, regional yields. At the field scale, the model accurately, without calibration of soil properties, simulates the soil water content and salinity (RRMSE less than 10%). Simulated soil nitrate concentration was not close to observed values (RRMSE of 54%) but the latter was also associated with a large variability. At the regional scale, the model offered an overall good integrated performance in simulating yield in the area under evaluation. For rainfed crops the regression line between simulated and observed yield is close to 1:1, however the model underestimates slightly simulated yield for the irrigated crops.

Keywords. Cropping System, Tunisia, Crop Modelling, Agronomic Units, soil Map Units.

INTRODUCTION

Much progress has been made in developing models that simulate the growth and development of crops under various conditions: CropSyst (Stöckle et al., 2003), APSIM (McCown et al., 1996), DSSAT (Jones et al., 2003), EPIC (Williams et al., 1989), GRASIM (Mohtar et al., 1997). Most of those models are designed to operate at the field scale using point data from specific sites; thus, model output is site-specific (Hartkamp et al., 2004; Shrikant et al., 2002).

There are clear advantages in adopting field scale crop simulation models to analyze regional and watershed level agricultural production, because agricultural recommendations and policies are generally implemented at this scale (Moen et al., 1994; Chipanshi et al., 1999). Integrating geographic information systems (GIS) and crop models is attractive because it allows simultaneous evaluation of spatial and temporal phenomena (Hartkamps et al., 2004). A handful of studies have been carried out (Kunkel and Hollinger, 1991; Van Lanen et al., 1992; Moen et al., 1994; Haskett et al., 1995) using crop simulation models linked to a GIS for regional or watershed yield simulations using region-specific representative soils types, crop varieties, and planting times. In these studies, weather inputs are generally obtained from local stations representative for the region, and soil characteristics required for the simulation are generally estimated from texture data using pedotransfer functions. Adopting this empirical approach for the soil characterization implies that the model must be, in principle, evaluated and calibrated at each point of the studied area. Therefore, soil mapping and characterization of soil units at the field and watershed scales is still a major challenge to the proper use of crop/cropping system models. The difficulty in this modeling challenge arises from two conceptual soil science questions:

- The physical equations and parameters used for soil modeling, such as the soil moisture characteristic curve, the soil water content at field capacity and wilting point, the conductivity curve etc., are still empirical; as they do not refer to the soil structure and its hierarchical levels of organization (Braudeau et al. 2004a, Braudeau and Mohtar 2007, Braudeau et al. 2005).
- Definition and map delineation of soil functional types is an open problem, depending on the approach chosen for characterizing soil types and on the scale at which this characterization is conducted.

To overcome the need to define a primary soil mapping unit and to correctly estimate soil hydraulic parameters, a new procedure was developed and tested in a watershed in Tunisia. Specifically, the objectives of this paper are:

1. Define a procedure to spatially characterize the soil organization based GIS and the study area to further evaluate regional agricultural management options;

2. Calibrate a cropping system model for agricultural production under water, nitrogen and salt stress conditions, and various management strategies;
3. Test the capability of the cropping simulation model to estimate agricultural production using the GIS developed in objective 1.

1. MATERIALS AND METHODS

1.1 THE CEBALAT IRRIGATED AREA

The Cebalat irrigated area, a 3200 ha in Eastern Tunisia, was created for the reuse of wastewater in irrigated fodder and cereal crops near the capital city, Tunis. However, the use of treated saline wastewater showed a risk of soil degradation (Hachicha and Trabelsi, 1993), made worse by the presence of a perched saline water table. Agricultural systems in the area are characterized by a great diversity of agricultural management, in terms of crop rotations and of the amount of water and nitrogen applied (Braudeau et al et al., 2001). The traditional crop rotation system is based on rain-fed cereals and forages during winter and maize and sorghum forage in the summer. The summer crops are irrigated with treated wastewater. Yield varies significantly from year to year based on the effect of weather, soil types, and farm management on soil salinity and availability of water and nitrogen e.g. the standard deviation of the soft wheat yield is 0.25 t/ha (average yield calculated for the period 1995-2000 is 2 t/ha) (Bahri 1994; Hachicha et al., 1997; Braudeau et *al*., 2001). Long-term meteorological data (1970 -2000) indicate that the region is characterized by irregularity and variability in seasonal rainfall and yearly distribution (standard deviation of 133mm/year) (Loukil *et al*., 2001).

Thirteen areas (≅ 20ha each) within the Cebalat irrigated area were chosen by the CRDA (Commissariat Régional du Développement Agricole) for a bi-annual survey of the watershed from 1996 to 2001. In each area, each field was characterized by crop rotation, planting, clipping and harvesting dates, dates and amounts of irrigation, nitrogen fertilizer and pesticide applied, and the yield. Five areas (from 1 to 5) were chosen among them representing all soil and rotation variability in the Cebalat area.

1.2 DEFINING THE AGRONOMIC UNITS

The aim of this section is to present the methodology and the steps that are followed to establish the *Agronomic Units* which are the superposition of soil map units, farm boundary, and cropping system. The agronomic unit defines the spatial distribution of unique combinations of individual data unit sets. Attributes associated with each data unit were stored in a database management program, which was used as input for the simulation model. Each of these units is therefore represented by the superposition of i) the soil information system mapping developed according to the systems approach, ii) the farm boundary, and iii) the cropping system (land use, rotation, crop management…). This approach has the advantage of a continuous representation of the system organization under and above the soil surface, from the primary ped (soil) to the crop (rotation and management).

1.2.1 Soil information system mapping procedures

A geo-referenced soil information system for the studied zone in the lower valley of the Medjerda River was developed based on the work of Braudeau et al. (2001) addressing the two questions introduced in the introduction section, namely; the empirical nature of parameters used in soil modeling and the declination of functional soil unit.

Regarding the definition and the delineation of the primary soil map unit, Braudeau et al., (2001) showed that an optimal delineation of these primary soil map unit can be obtained using the systems approach. In this approach, several nested levels of the natural landscape organization are represented on the same map namely: relief units, geomorphologic units and primary soil units (figure 1). These primary soil map units are represented by a pedon, where the hydro-structural properties are the same everywhere in the unit.

As for the hydrostructural characterization and modeling of these soil units, a new methodology based on the shrinkage curve measurement (Braudeau et al. 2004a) was adopted. The physically-based and independent parameters of the shrinkage curve characterize the hydro-functional organization of the pedostructure (soil fabric of the horizon) (figure 2). In addition, the standard soil characteristics, such as the wilting point or the field capacity, are linear combinations of these parameters (Braudeau et al. 2005; Braudeau and Mohtar 2006) and physically-based equations of the soil functioning, such as the matric water potential or the swelling pressure, are also expressed using these parameters (Braudeau et al., 2005; Braudeau and Mohtar, 2006).

According to the principles above, pedological cartography and characterization of the Cebalat area was conducted in order to build a spatially referenced soil information system for soils in the studied area (Derouiche et al., 2001). The existing soil map of the zone (Maury, 1963) was checked and restructured for presenting three nested levels of organization (primary soil units, geomorphology and relief) (figure 1). This reorganized soil map, along with the new physical characteristics of the soil units (hydrostructural parameters), were then introduced in the GIS containing all information about the infrastructure of the Cebalat irrigated area. The pedological study (Braudeau et al., 2001) highlighted three soil types: vertic, calcareous, and weakly saline that are differentiated by their hydro-structural behavior (figure 2). This differentiation was obtained with the help of the canonical discriminant analysis, using the hydro-structural parameters as descriptive variables of the soil types according to the methodology of Braudeau and Mohtar (2006). Table 1 shows the average value of the three soil parameters required by CropSyst: the specific volume at field capacity (V_D), and the water contents corresponding to the field capacity W_{FC} and the permanent wilting point, W_{PWP}, for each soil type. These three parameters were calculated directly from the hydro-structural parameters (Braudeau et al., 2004b, Braudeau and Mohtar, 2006). The fourth soil parameter which is needed for the soil-water modelling by CropSyst is the hydraulic conductivity at saturation, k_{sat}, which was estimated from the particle size analysis (Table 1) using the pedotransfer function provided by CropSyst. Note that, among these four parameters, only k_{sat} is empirical and may be calibrated as necessary.

1.2.2 The farm boundaries and survey

To establish the farms boundary in the five areas, two SPOT images (1996 and 1998) geo-referenced in Tunisia Lambert System and two aerial photos at 1:20000 and 1:10000 scales were used (Braudeau et al., 2001). GIS tools were used to store spatially-referenced data such as soil characteristics, land use, precipitation, planting dates and crop management. Each field was characterized from 1996 - 20001 by a land use and a crop management showing planting date and amount and date of irrigation and fertilization (figure 3). The agents of the CRDA carried out two surveys every year between 1996 and 2001. The first survey was conducted in March and April to establish the land use for winter rainfed crops and the second survey was conducted between July and August for the summer crops. For each crop, the agent noted the amounts of irrigation water, nitrogen fertilizer and pesticide applied, the planting and harvest dates, and the yield.

1.3 THE SIMULATION MODEL

1.3.1 CropSyst

The CropSyst (Cropping Systems) model (Stöckle et *al*., 1994; Stöckle et *al*., 2003) was used to simulate the cropping systems in the study area. CropSyst implements modules capable of simulating crop response to a wide range of weather, soil and management conditions using daily time steps, for periods ranging from one year to a hundred years. CropSyst is a multi-year, multi-crop, daily time step crop growth simulation model, developed with emphasis on a friendly user interface. It includes utilities to link to spatial tools and a weather generator. It allows simulating the soil water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and pesticide fate.

Crops are simulated using a generic crop simulator, in which some processes (e.g. photoperiod response, vernalization) can be switched on-off using appropriate parameter values. CropSyst simulates plant growth as potential growth, applying water, nitrogen, and temperature stresses. Water infiltration and runoff is estimated either using the soil curve number approach (USDA, 1972) or a mechanistic approach which accounts for soil surface roughness. Water redistribution in the soil profile is simulated either using the cascading approach (in it simplest form, without travel time) or using a finite difference solution of Richard's equation, in which the soil is subdivided into layers and the numerical solution considers the centre of layers as nodes. Appropriate boundary conditions are defined to simulate irrigation, free drainage, and a shallow water table. The nitrogen transformations implemented in CropSyst include net mineralization, nitrification and denitrification, which are simulated using first order kinetics (Stockle and Campbell, 1989).

Salinity effects on crop water uptake are accounted for by the osmotic potential of total soil water potential and a direct effect on roots conductance. Processes are affected by weather, soil characteristics, crop characteristics, and cropping system management options including crop rotation, cultivar selection, irrigation, nitrogen fertilization, pesticide applications, soil and irrigation water salinity, tillage operations, and residue management (Donatelli et *al*, 1997).

Among cropping systems models, CropSyst was chosen both because it has some peculiar features not available in other programs, and because its includes most of the features needed in this study in one package. In detail:

- the crop part is based on a generic crop simulator, which suggested that calibration for new species (as berseem) would have been easier,
- it allows simulation of perennial crops as alfalfa,
- it simulates salt in the soil, including irrigation with fresh and saline water,
- it simulates water redistribution in the soil profile with numerical solution of Richard's equation, which could be used in case of water table to simulate upward movement of water,
- it allows simulating a broad range of agricultural management,
- it is coupled to a GIS system,
- it has a user friendly interface.

1.3.2 The ARCinfo-CropSyst Cooperator (ArcCs)

ArcCs facilitates GIS-based CropSyst simulation projects by using polygons derived from objects, procedures, and functions to simulate the ArcView or ArcInfo. Each polygon represents a land block fragment. ArcCS uses the polygon attribute table produced by the GIS software to identify, generate and run a simulation scenario for each unique land block fragment. A new polygon attribute table of CropSyst output variables is generated, which can be used by Arc/Info or ArcView to produce maps of the CropSyst outputs (Stockle and Nelson, 2003).

Simulations of CropSyst were conducted for five areas for the 13 areas surveyed by the CRDA. The inputs for the model were different sets for each agronomic unit (combination of soil, land use and management practices) between 1996 and 2001. The GIS database was used as data input for the model using ArcInfo-CropSyst Cooperator (ARCCS) program (Stöckle and Nelson, 1993), which controls model execution.

1.3.3 Model parameters

Table 2 summarizes the crop input parameters which can be either i) measured during the season 1999-2000 (M), ii) available in the literature (L), or iii) calibrated (Cal) to match model output against observed field. CropSyst inputs were set based on:

<u>Parameters input</u>

- <u>Soil</u>: The bulk density and water contents at field capacity and wilting point were determined using data of the Soil-GIS. The hydraulic conductivity was estimated from texture using the Pedotransfer functions proposed by SoilPar software (Acutis and Donatelli, 2003).
- <u>Weather</u>: The daily maximum and minimum temperatures and precipitation were available at the experimental site. Solar radiation was calculated from sunshine duration using the Angström formula (FAO, 1979). Potential evapo-transpiration was calculated using the Priestley-Taylor method (Priestley and Taylor, 1972).
- <u>Management</u>: The amounts, salinity levels, and timing of irrigation, initial soil water and nitrate content, and planting and harvest dates were collected at the experimental site.
- <u>Crop:</u> The phenological stages, growth and morphologic characteristics such as maximum rooting depth, and specific leaf area were compiled for use in the simulation.

<u>Parameter calibration</u>

Only the biomass-transpiration coefficient (KBT) and the conversion of light to above ground biomass coefficient (KLB), were determined by calibration since the model were very sensitive to these parameters under arid conditions (Stöckle and Nelson, 1993 ; Stöckle et al, 2003), For each crop, the CropSyst model was calibrated continuously from January 1999 to December 2000 against data collected during the two growing seasons under no nitrogen, water or disease stresses. Values of KBT and KLB were adjusted within a reasonable range of variation (Donatelli et al., 1997) based on previous research, knowledge or experience in order to have the best model estimation of the biomass accumulation observed for each crop in calibration experiments (Donatelli et al., 1997). Adjustment stopped when further modification of crop parameters would generate little or no improvement on the basis of the relative error a statistical measure we used to quantify the degree of fit in the relationship between measured and simulated aboveground biomass (Cabelguenne et al., 1990).

1.4 FIELD EXPERIMENTS: SOIL AND CROP VARIABLES MEASUREMENT

Experiments were conducted in order to calibrate and evaluate the CropSyst model. Three bi-annual rotations were selected. Following expert knowledge and farmer practices, a list of representative bi-annual rotations for each soil type was defined:

1. rainfed winter cereals (wheat, barley, oats) follows by maize and sorghum (grain or forage) in the summer in the vertic and calcareous soils;
2. irrigated winter forage (mainly bersim) follows by fallow in the vertic soil, and
3. perennial alfalfa crop grown for 3-4 years in the saline soil.

Based on this typology, data from a 2-year experiment (1999 and 2000) conducted at fields of six farmers in the five areas were collected (Table 3). Each field (1-1.5 ha) was divided into five sections of 0.2 ha. Crop management data used included amount and time of application of water and nitrogen, sowing date, harvest and clipping dates.

Daily meteorological data were recorded at Cherfech station. Within the growing season, from June 1999 to May 2000, 418 mm of rain were recorded, of which 300 mm occurred between November and January. During the summer, air temperature reached 40 °C with dry and hot wind.

For each phenological crop stage, four replications of soil and crop samples were taken of 1 m^2 each, successively for each section of the field. To avoid border effect, samples were chosen from the center of the field. Soil salinity, total nitrate and gravimetric soil moisture in the root zone for each

0.20 m increments of the soil layer in the upper 1 m were measured. Soil samples were taken at different phenological stages. Leaf area index, above ground biomass at different phenological stages and yield were measured for each crop. To generate a representative sample, four sub-samples were combined for each sample. Water table level, nitrogen and salinity were measured by access tubes inserted in each field. Water from irrigation and water table was sampled every 15 days to measure salinity and nitrate concentration. Water table levels were measured at the same date using a sounding rod meter.

1.5 MODEL USE AT FIELD AND AREA LEVELS

Calibration and evaluation of the crop model was done at the field level. Data from the six experimental fields were divided in two independent groups of data sets:

1. For the crop model calibration, data on yield or biomass for the forage crops at experimental field are used to calibrate K_{BT} and K_{LB} by minimizing the difference between simulated and observed biomass.
2. For testing the model on soil variables, the calibrated model is run without changing the soil parameters. The measured values of water, nitrogen and soil salt content at experimental field were then compared to the simulated values.

Following field scale simulations, evaluation of the capability of the calibrated model to simulate yield at the regional level was conducted. A large range of agronomic conditions were identified at the regional levels, combining crops, soils, crop management (mainly water and nitrogen) and weather (rainfall), thereby allowing evaluation of the model for a wide range of conditions. Grain yields and above ground biomass were the only variables measured for this range of agronomic conditions with a sufficient precision to be used for the evaluation of the model at the regional scale. Simulated and observed above ground biomass (forage crops) or yield (grain crops) for five growing seasons (1996-

2001) obtained from CRDA data for all fields and rotations were compared. Rotations were continuously simulated using ARCCS program for each “agronomic unit” starting from January 1996 to December 2001.

The agreement between simulations and measurements is evaluated using regression analyses and statistical indices proposed by Loague and Green (1991), namely; the root mean square error (RMSE), the parameters of the linear regression equation between observed and predicted value, and the relative root mean square error (RRMSE). Based on this analysis, the RRMSE of 10% can be considered as an acceptable level for calibration/validation (Loague and Green, 1991). The range of the later Wilomtt Index of Agreement (d) is between -∞/+∞, with an optimum value of unity.

2-RESULTS AND DISCUSSION

2.1 CALIBRATION AND SIMULATION RESULTS AT THE FIELD SCALE

2.1.1 Crops

Calibrated model parameters are shown in Table 4. Calibrated K_{BT} (biomass transpiration coefficient) for C_4 crops are about twice that of C_3 crops due to their higher efficiency of photosynthetic conversion. This result is consistent with those by Squire (1990). Calibrated K_{BT} for maize (8 kg.KPa/m) are lower than those of Tanner and Sinclair (1983) (8.2-12 kg.KPa/m) but higher than those determined by Stöckle and Nelson (1997) 7 kg.KPa/m. For forage alfalfa crop the calibrated K_{BT} (4 Kg.KPa/m) it is well in the range values of 5 and 3.5 kg.KPa/m determined, respectively, by Confalonieri et al. (2001) and Tanner and Sinclair (1983). For the cereal crops (barley, wheat and oats), the calibrated K_{BT} values is the same of that determined by De Wit (1978) for oats (4.5 Kg.KPa/m), Stöckle and Nelson (1997) for wheat (5.8 Kg.KPa/m) and Jorgensen (1991) for barley (4.6 Kg.KPa/m). For berseem the value of 3 Kg.KPa/m was used (default value recommended for 51 C_3 plants by Stanhill (1986)). The values of calibrated K_{LB} (radiation-use efficiency) for maize, sorghum and wheat were almost the same as those cited by Kiniry et al (1989) for maize (3.6-4.5 g.MJ), by Rosenthal et al (1989) for sorghum (2.9-3.46) and by Gregory and Eastham (1996) and Yunusa et al (1993) for wheat (2.92-3.24). For barley, the calibrated K_{LB} (2.5 g.MJ) was inferior to the value (4g.MJ) cited by Jamieson et al (1995). For alfalfa and oats K_{LB} values were default selected from CropSyst manual without calibration.

Table 4 presents a comparison between measured and simulated grain/biomass yield for the 7 crops. For all crops, mean simulated yields/biomass were close to the mean measured yield/biomass. For maize, barley, oats and berseem, the model gave a good estimation of yields/biomass, with a relative root mean square error lower than 10%. The results were less satisfactory for wheat and maize or sorghum forage crops. The RRMSE values were 13% of the observed average. The lowest correlation was obtained for alfalfa with a RRMSE of 18%. For all crops except for alfalfa and to a lesser degree for sorghum, barley and maize, the slopes and intercepts of the regression equations for the measured and simulated yields/biomass followed the 1:1 line closely (table 4).

2.1.2 Soil water, salt and nitrogen

The simulated soil water content for the three soil types closely followed the 1:1 line when plotted against the experimental data with a high correlation between observed and measured ($R^2 > 0.8$) (Table 5). Statistical analysis indicated that CropSyst predicted soil water content with acceptable accuracy, showing high indices of agreement (d) and RRMSE less then 10%. However, soil water simulation resulted more accurate in vertic soils compared to saline and calcareous. Indeed, the soil water content in calcareous soil presented the lowest correlation with measured values ($R^2 = 0.8$) compared to the simulation obtained in the vertic and saline soils.

Average salt concentration of the top one meter soil layer were simulated and compared to measured values (Table 5). The index of agreement (d) is better for the vertic soil than that of the saline and the calcareous soil. For the vertic soil, CropSyst overestimates soil salinity concentration, as shown in the 1:1 line comparison. The lowest agreement with measured values was obtained for the calcareous soil (d =0.91), probably because CropSyst slightly underestimated the soil water content in this type of soil.

The measurements of soil salt content confirm the higher levels of soil salinization described by Hachicha and Trabelsi (1993) in the “saline” soils. Indeed, the average soil salinity is usually exceeding 4dS/m. In the vertic soil, the soil salinity reached 14 dS/m (data not shown), a level too high for the majority of annual crops (Mass and Hoffman, 1977).

Table 5 shows a comparison between measured and simulated nitrogen in the soil profile. These results show that the model is simulating soil nitrate dynamic with a satisfactory accuracy for vertic and calcareous soil, with a RRMSE lower than 25%. However, the model results were not good for the saline soil giving RRMSE of 54%. It must be pointed out that field measured data of soil nitrogen content were affected by a large variability, and this increases the uncertainty of model evaluation. In fact, nitrogen content in the form of nitrates showed a large variability (SD of sample measurements is reported in Table 6).

2.2 SIMULATION AT REGION LEVEL

CropSyst gave a good simulation of grain yield (Table 7). RRMSE values were lower than 10% of the observed average in the case on barley and berseem and 13% to 18% of the observed average in the case of wheat, maize, sorghum, oats and alfalfa. Index of agreement was high for all crops (0.9) except for alfalfa. For rainfed crops the slope of the regression line between simulated and observed yields is close to 1:1 (Figure 5). The model underestimates biomass/yield for the irrigated crops: berseem, maize and sorghum both for forage and grain. Concerning alfalfa, the results are less satisfactory, but rather acceptable considering the perennial characteristic of the crop. The CRDA data collection protocol contributed to the sources of error as compared to the model simulation. In the practical, farmers clip at the beginning of spring when the alfalfa starts growing. This cut serve only to stimulate the growth of the crop. Even if this limitation of model simulation does not significantly influence the total biomass, it has certainly an effect on crop growth dynamics and biomass accumulation.

CONCLUSION

We have tested the new concept for GIS based soil information system build according to a soil mapping and characterization following the system approach. The characterization is a spatially organized soil data with functional parameters and framework consisting of primary soil map delimitations. CropSyst was used to simulate soil water dynamics, soil salinity and nitrogen leached at the field level and was scaled up to the area level to simulate yield. This GIS based soil information system offers two major advantages to the agronomic models: i) a correct representation of the internal hydro-structural organization and functionality of the soil unit (pedon), and ii) a spatial mapping of the primary soil units.

The calibration of CropSyst was satisfactory for the majority of the crops. Soil water was correctly simulated, although the calcareous soils resulted in the worst performance among the three soils. Salt were not simulated correctly in the "calcareous" soils. This can be due to the performance of water simulation in calcareous soils (the worst compared to other soils). The less satisfactory result was nitrogen simulation in saline soils, possibly because salt content affects nitrogen transformation processes in ways not accounted for by CropSyst. We concluded that nitrogen management should not be investigated using CropSyst on saline soils.

Creating mapping units using the proposed approach, based on a physically based soil characterization, lead to a classification and clustering of soils accounting for a coherent set of hydraulic characteristics. The characterization of the internal soil functioning constitutes a first step for a new approach for soil water-soil structure modelling. Recently, a new model, Kamel, was developed for a such simulation, allowing also the use of mapping soil units according to soil surface proprieties detected by satellite sensor systems (Braudeau et al., 2007).

CropSyst estimates of biomass and yield on mapping units satisfactorily represented field measured data pooled by the mapping units defined. Although the system should not be used to investigate nitrogen management options in saline soils, it can be used to study innovative irrigation management strategies.

Although the indirect test of the mapping procedure made via CropSsyst simulating crop biomass and yield cannot be considered an exhaustive evaluation, it is promising and suggests a further test in completely different environments. Future work should investigate the performance of the model in simulating nitrogen transformation in saline soils, possibly referring to other approaches which do not simplify microbial mediated process implying, as CropSyst does, that the microbial community is not limiting and driven only by water and temperature.

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Table 1. Soil texture and parameters required for the CropSyst model. The soil parameters were established using the shrinking curve parameters (Braudeau and Mohtar, 2005);

Soil classes and texture (discriminate analysis)	User Name	Texture			Soil parameters		
		Clay	Loam	Sand	VD	WCFC	WCWP
			(%)		cm^3/g	m^3/m^3	
I – Silt clay loam	Vertic	31.40	60.20	5.70	0.81	0.43	0.15
II - Loam	Calcareous	23.60	37.80	35.60	0.71	0.34	0.11
III – Clay loam	Weakly saline	28.60	48.40	35.60	0.76	0.38	0.12

VD is the specific volume at field capacity, WCFC is the water content at field capacity and WCWP is the water content at wilting point.

Table 2- Crop input parameters used in CropSyst simulation. Parameters were measured experimentally (M), extracted from the literature (L), or from calibration (Cal).

		sorghum	maize	wheat	barley	Oats	berseem	alfalfa
Degree days emergence (°C.d)	M	120	120	100	100	150	100	100
Degree days begin flowering (°C.d)	M	1120	1120	1000	600	-	-	-
Degree days peak LAI (°Cd)	M	1140	1040	1040	632	-	-	-
Degree days begin grain filling (°C.d)	M	1400	1400	1060	732	-	-	-
Degree days maturity (°C.d)	M	1860	1900	1500	1000	-	-	-
Base temperature (°C)	L	8	8	0	0	0	3	5
Cutoff temperature (°C)	L	25	30	22	25	22	22	25
Phenologic sensitivity to water stress	L	1	3	1	0.5	1	2	1
Maximum root depth (m)	L	1.8	1.5	1.5	1.6	1.5	1	1.8
Maximum LAI	M	5	6	5	5	5	7	5
Specific leaf area (m^2/kg)	M	26	22	22	22	22	26	22
Stem/leaf partition coefficient	M	2.5	2.5	3	4	3	3	4
Leaf duration (°C.d)	L	1000	850	700	1000	-	-	-
Leaf duration sensitivity to stress	L	1	3	1	1	1	3	2
Solar radiation extinction coefficient	L	0.48	0.48	0.48	0.48	0.48	0.48	5
ET crop coefficient	L	1	1.1	1.1	1	1.2	1.2	1.2
Maximum water uptake rate (mm/day)	L	12	16	10	10	10	8	14
Critical canopy water potential (KPa)	L	-1200	-1200	-1300	-1500	-1500	-700	-1300
Wilting canopy water potential (KPa)	L	-1800	-1800	-2000	-2200	-2200	-1600	-2000
Biomass-transpiration coefficient (Pa)	Cal	8	8	5	3.5	5	4.5	4.5
Radiation use efficiency (g/MJ)	Cal	3	4	3	2.5	3	2.5	2.5
Maximum harvest index, HI	L	0.5	0.43	0.5	0.48	-	-	-
HI sensitivity to stress at flowering	L	0.1	0.4	0.1	0.1	-	-	-
HI sensitivity to stress at grain filling	L	0.1	0.4	0.1	0.05	-	-	-
φ0,50 for 50% yield reduction	L	-233.1	-232.5	-341.8	-514.5	-514.5	-246.7	-341.3

Table 3. Crop species, area, irrigation system and soil types for each field used for calibration experiments. The experiments were run on 6 fields with 4 replications for each soil and crop sample.

Soil	Summer 1999		Winter 2000		Area (ha)
	Crops	Irrigation system	Crops	Irrigation system	
Vertic	Forage maize	Sprinkler	Wheat	Rainfed	1
	Forage sorghum	Sprinkler	Wheat	Rainfed	1
	Fallow	No irrigation	Berseem	Sprinkler	1.5
Weakly Saline	Alfalfa	Sprinkler	Alfalfa	Sprinkler	1
Calcareous	Grain maize	Flooding	Barley	Flooding	1.5
	Sorghum maize	Flooding	Oats	Flooding	1.5

Table 4- Model calibration: Estimation of above ground biomass-transpiration coefficient "KBT (kg.kPa/m)" and light to above ground biomass conversion coefficient "KLB (g/MJ)" values.

Crops	N	Variables	Observed (kg/ha)	Simulated (kg/ha)	RRMSE (%)	Slope (%)	Intercept (kg/ha)	R²	KBT Value (Kg.KPa/m)	KLB Value (g/MJ)
Maize	18	Yield	4062	4152	7.0	0.83	601.62	0.92	8.0	4.0
Sorghum	18	Yield	7950	8098	13.0	0.95	183.68	0.84	8.0	3.0
Wheat	15	Yield	2390	2446	13.0	0.86	275.71	0.98	5.5	3.0
Barley	12	Yield	2156	2198	8.0	0.940	76.15	0.86	3.5	2.5
Oats	12	Biomass	4908	4973	7.0	1.04	-217.69	0.98	5.0	2.0
Alfalfa	24	Biomass	19767	20934	18.0	0.50	10967.00	0.64	4.0	2.5
Berseem	15	Biomass	22720	22682	3.0	0.80	4364.50	0.91	4.0	2.5

N: number of observations

Table 5- Model Validation at the field scale: statistical summary data comparing water, salts and nitrogen soil content observed data vs. simulated values. The observed values were obtained from field experiments during two growing seasons in the Cebalat area.

	N	Observed average	Predicted average	RRMSE	Wilmott index of agreement (d)	Slope	Intercept	R²
Water		(m^3/m^3)	(m^3/m^3)	(%)			(m^3/m^3)	
Vertic	187	0.2	0.2	8.5	0.97	1.01	-0.0012	0.88
Calcareous	165	0.17	0.17	9.5	0.97	0.82	0.030	0.8
Saline	86	0.16	0.16	9.6	0.99	1.06	-0.007	0.93
Salts		(dS/m)	(dS/m)	(%)			(dS/m)	
Vertic	60	5.09	5.18	9.9	0.99	1.04	-0.057	0.97
Calcareous	48	4.87	4.85	2.8	0.91	0.75	1.167	0.71
Saline	19	4.61	4.8	7.6	0.93	0.93	0.499	0.71
Nitrogen		(kg/ha)	(kg/ha)	(%)			(kg/ha)	
Vertic	48	5.16	5.18	24	0.99	0.98	0.062	0.98
Calcareous	20	4.76	4.77	18	0.99	0.98	0.062	0.98
Saline	16	3.43	2.67	54	0.99	0.87	0.492	0.87

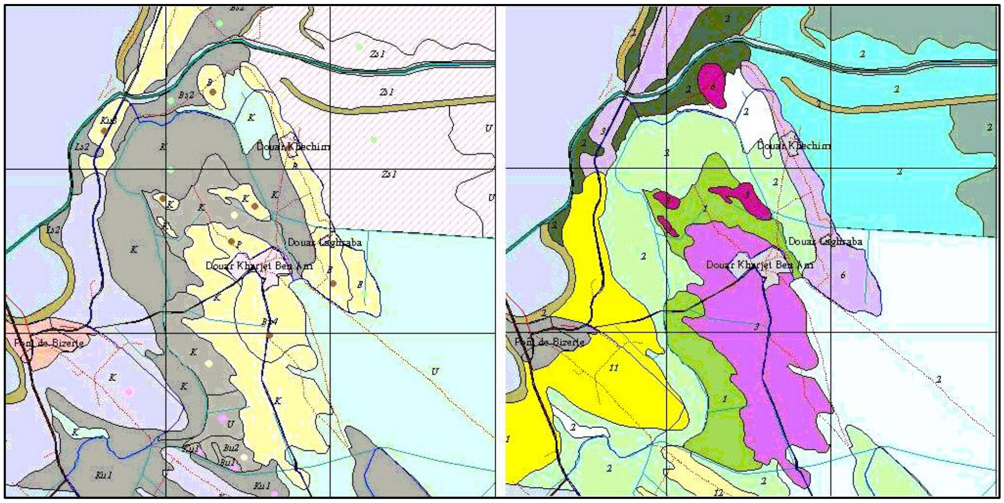
Table 6- Average and standard deviation of measured soil Nitrogen content for several crop successions and dates. The colored cells represent measurements with high values of standard deviation compared to the average.

	Dates of sampling						
Wheat/maize	**07/01/1999**	**10/06/1999**	**09/08/1999**	**16/02/2000**	**27/03/2000**	**17/05/2000**	**01/06/2000**
Average (kg/ha)	0.08	5.488	1.18	7.39	0.96	1.32	0.63
Standard deviation/kg/ha)	0.05	9.78	1.97	6.38	1.02	1.37	0.76
Alfalfa	**06/05/1999**	**28/02/1999**	**10/04/2000**	**23/05/2000**			
Average (kg/ha)	3.17	0.87	8.85	3.53			
Standard deviation (kg/ha)	1.95	1.62	4.84	2.84			
Fallow/berseem	**07/01/1999**	**10/09/1999**	**16/02/2000**	**27/03/2000**	**08/05/2000**		
Average (kg/ha)	3.25	38.88	1.43	1.22	0.87		
Standard deviation (kg/ha)	1.14	18.52	1.73	1.55	0.93		
Sorghum/barley	**07/01/1999**	**26/08/1999**	**04/02/2000**	**24/03/2000**	**05/05/2000**		
Average (kg/ha)	1.84	6.04	7.86	0.72	7.38		
Standard deviation (kg/ha)	0.76	7.68	8.31	1.28	10.18		
Sorghum/oats	**02/02/2000**	**03/04/2000**	**17/05/2000**				
Average (kg/ha)	14.97	10.03	19.02				
Standard deviation (kg/ha)	8.26	6.34	10.52				

Table 7- Model validation at the zone scale: statistical summary data comparing biomass and yield observed data with simulated values using the ARCCS program. The observed values were obtained from CRDA data for 4 growing seasons in Cebalat area.

Crops	Variables	N	$\bar{O}$ (kg/ha)	$\bar{P}$ (kg/ha)	RMSE (kg/ha)	RRMSE (%)	d
Wheat	Yield	57	1872.46	1743.16	251.29	13	0.96
Barley	Yield	51	2090.00	2013.94	165.63	8	0.97
Maize, sorghum grains	Yield	12	5000.00	4332.26	845.30	17	0.96
Maize, Sorghum forage	Biomass	28	8488.93	7641.19	1210.18	14	0.94
Berseem	Biomass	45	24391.00	23766.3	1127.74	5	0.95
Oats	Biomass	49	5218.16	5295.55	916.22	18	0.97
Alfalfa	Biomass	9	21244.36	21005.56	2994.63	14	0.86

N: number of observations, $\bar{O}$: average measured yield or biomass, $\bar{P}$ **:** average simulated yield or biomass, RMSE: root mean square error, RRMSE: relative root mean square error, d: Wilmott index of agreement.



Primary soil map units Geomorphologic map units

Figure 1. Part of a pedological cartography and characterization of the Cebalat area based on the soil map of the zone (Maury, 1963). Example of primary soil map units nested in the Geomorphologic map.

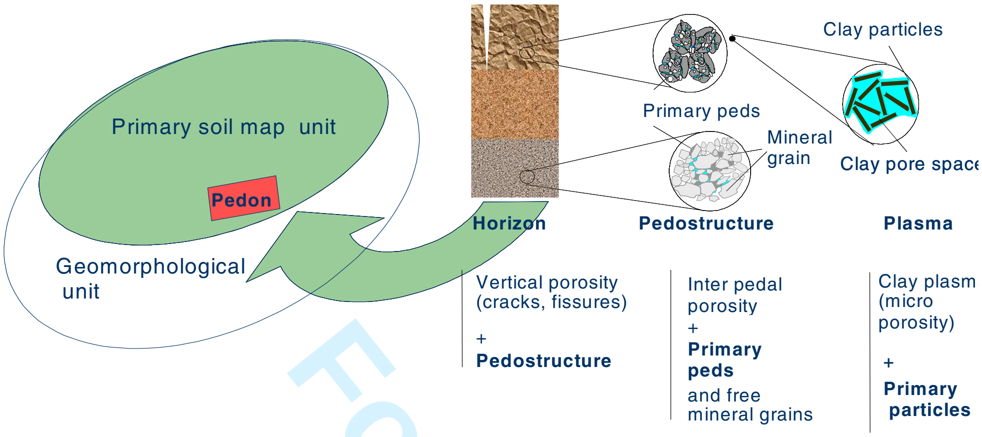


Figure 2. The different functional hierarchical units of the soil organization that can be recognized and characterized using the new methodology of hydrostructural characterization of soil (adapted from Braudeau and Mohtar, 2006)

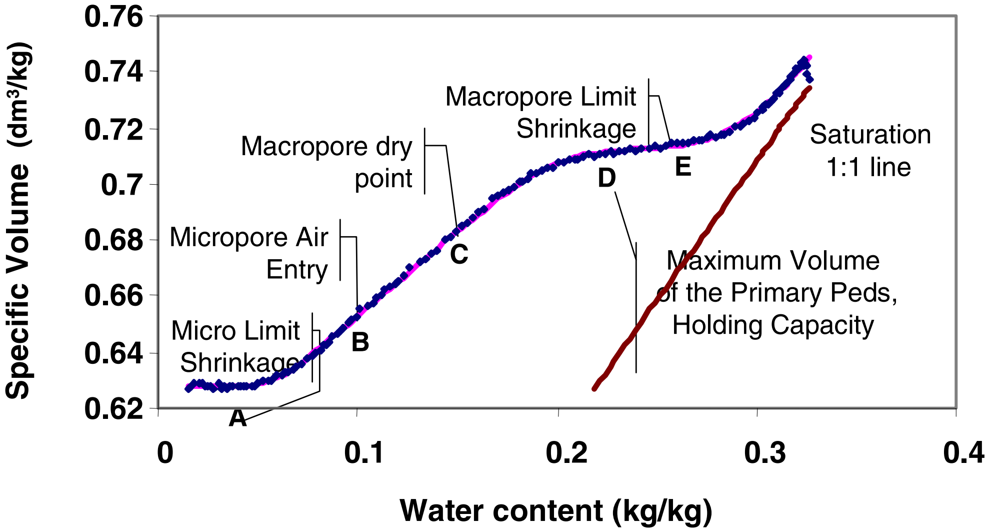


Figure 3. Measured shrinkage curve with its particular hydrostructural states which are the transition points of the shrinkage phases: A, B, C, D and E (Braudeau et al, 2004b)

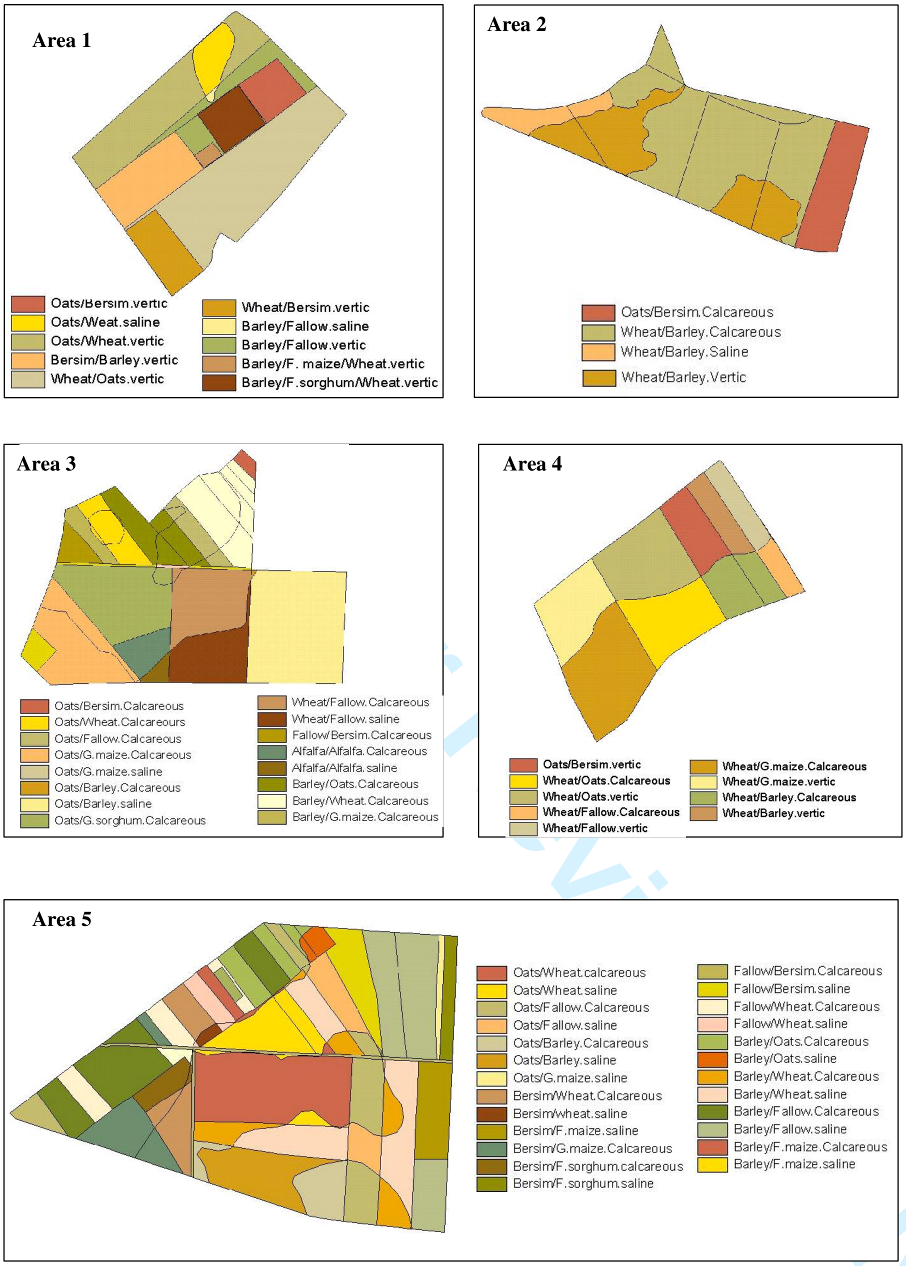


Figure 3. "Agronomic units" with the soil information system mapping and the farm survey for the retained area and the year 98/99. The first crop in the rotation represents a previous crop and the second the current one.

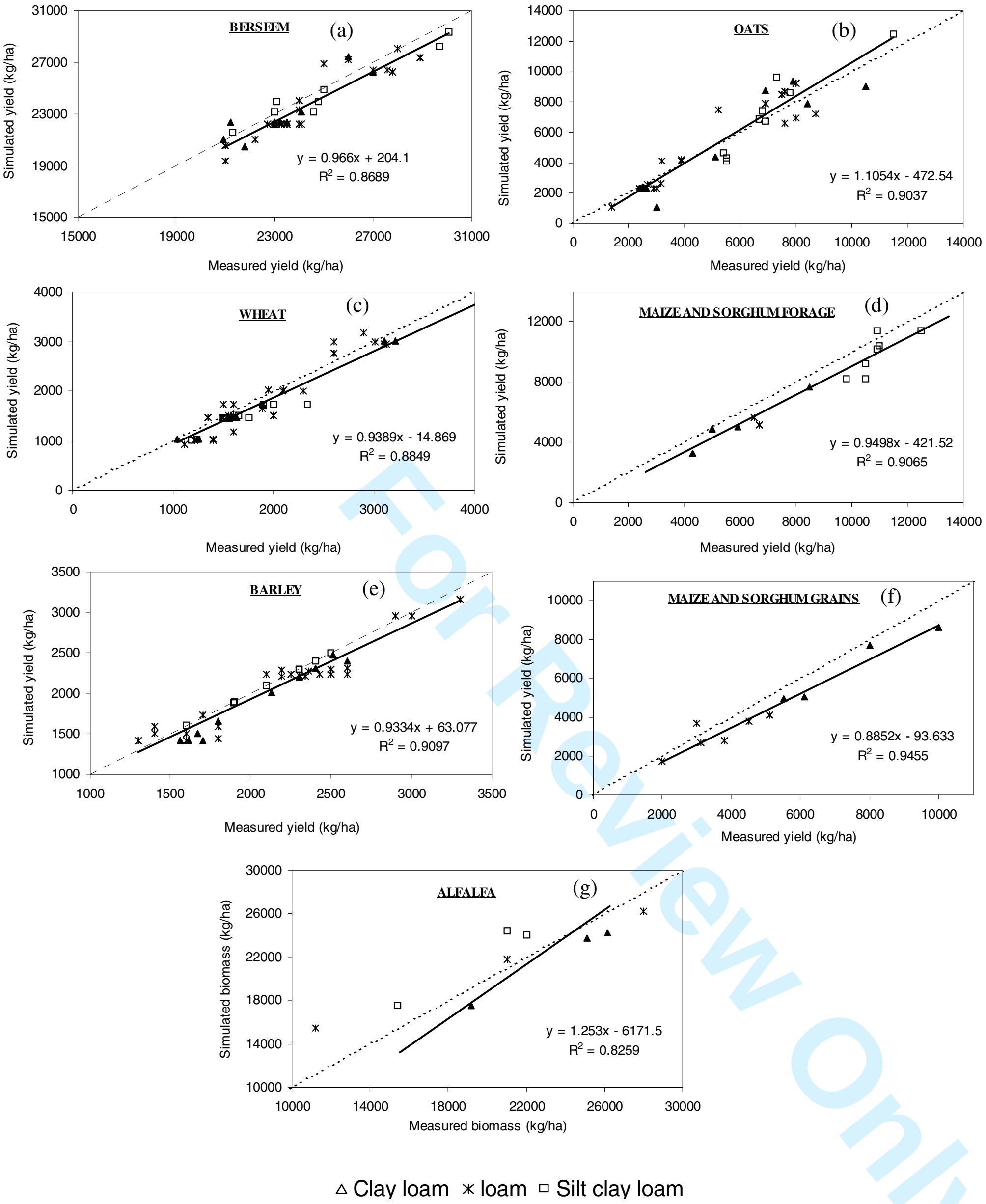


Figure 5. Predicted (line) and observed (symbols) yields in the areas for different soil type and crops (a, b, c, d, e, f, g).