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Ph.D. in Agricultural Ecology
XXIII Cycle

Modelling nitrogen dynamics in crop and soil: from site-specific to regional application in northern Italy

Ph.D. Thesis

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UNIVERSITÀ DEGLI STUDI DI MILANO

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Alessia Perego

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The aim of my Ph.D. work was to investigate the main factors related to N leaching from arable land under different pedoclimatic conditions and cropping systems in Lombardia plain. *In situ* monitoring and modelling analysis were defined to evaluate the potential N losses via leaching from arable land and the effect of agricultural management. At monitoring sites, representative of Lombardia arable land, data of soil, crop, water, and N-related variables were collected for a period from 2 to 5 years. Soil characterization, crop yield, leaf area index, harvest index, crop nitrogen uptake, soil water content and soil solution nitrogen concentration at different depths were measured over the monitoring period.

All the collected data were used to calibrate and validate the ARMOSA model. Such dynamic model was developed by our research team to predict N leaching risk from arable land in northern Italy. The calibration and validation procedures allowed to parameterize (i) pedological parameters related to soil water balance and nitrogen dynamics, such as mineralization, denitrification, volatilization, wet and dry atmospheric deposition, immobilization; (ii) six crops growth and development parameters which lead the gross assimilation of CO_2, leaf area index, stem and root elongation, respiration loss, nitrogen dilution curve, crop development based on growing degree days, dry matter partitioning, evapotranspiration and residuals calculation. The outstanding result was that crop, water and N-related variables were accurately simulated, being in full agreement with observed data.

Once calibrated and validated, ARMOSA model was applied at regional scale in order to evaluate the potential risk of N leaching. The model run over 20 years in 35 simulation units, obtained by dividing Lombardia plain in homogenous districts in terms of pedological, climatic and cropping systems features. Each

district was characterized by two representative soil types, meteorological observed data set, crop rotations according to the regional land use analysis, organic N load, calculated on the basis of livestock density.

With regard to results, similar or even higher N use efficiency resulted with increasing organic N supply and proportionally reduced mineral fertilization. In such way, N leaching decreased by half in maize-based forage systems. Moreover, the eventual choice to introduce a catch crop in rotation strongly contributed to minimize N leaching.

Credits evaluation

Courses:

- Elements of statistics.
- Instrumental analysis.
- Biogeochemical cycles.

Attendance at international/national congress:

- Anaerobic digestion: opportunities for agriculture and environment, 24-25 January 2008, Sesto San Giovanni, Milano, Italy.
- XI Convegno Nazionale di Agrometeorologia, 10–12 June 2008, San Michele all'Adige (Italy)
- X Congress of the European Society for Agronomy, Bologna, Italy, 15-19 September 2008.
- XVI Nitrogen Workshop: Connecting different scales of nitrogen use in agriculture. June 28th – July 1st 2009, Turin, Italy.

Oral presentation at international/national congress:

- From site-specific modelling supported by monitoring data to regional application. X Congress of the European Society for Agronomy, Bologna, Italy, 15-19 September 2008.

Attendance at seminars:

- Seminar: "Climate change and impact assessment on crops" (1 hour) and "Bioenergy crops: a contribution to a sustainable future?" (1 hour) and "Carbon dynamics in soil and carbon sequestration potentials" (1 hour), hold by Dr. Goetz Richter at University of Milano – Faculty of Agricultural Science. 26-27-28 September 2007.
- Seminar: "Basic and advanced geostatistics" (8,5 hours) hold by Prof. Alfred Stein at University of Milano – Faculty of Agricultural Science. 12-13-15 May 2008.

Poster presentation at international/national congress:

- **Perego, A.**, Acutis, M., Carozzi, M., Bernardoni E., Brenna S., 2010. Model forecast of N dynamics in Po Plain under different cropping systems provided for EU Nitrates Directive derogation. Proceedings of the 12th Congress of the European Society for Agronomy, Montpellier (Italy), August 29th-September 3rd: in press.
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Publication:

- **Perego**, **A.**, Basile, A., Bonfante, A., De Mascellis, R., Terribile, F., Brenna, S., Acutis, M., 2010. Nitrate leaching under maize cropping systems in Po Valley (Italy). Agric. Ecosyst. Environ., Submitted.
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- Interniship at ZALF - Leibniz Centre for Agricultural Landscape Research, Institute of Landscape Systems Analysis- Muencheberg (Germany), under the guide of K.C. Kersebaum. From April 19th to July 6th 2009.

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CONTENTS:

Chapter 1

Introduction

1.1. Nitrogen leaching in cropping systems

Nitrogen (N) is the element most plentiful in the atmosphere, as elemental nitrogen (N_2), and yet is the nutrient element most often deficient in agricultural soils (Godwin and Singh, 1998). This paradox occurs because N is the nutrient element most required in large amount by crops and because only a small part is in a form available to plant uptake. N fertilizers are widely employed in order to enhance the soil supply of such macroelement. The intensification of agricultural process involved higher nitrogen demand of crops because of the increasing of dry matter production, leading to negative effects on environment, especially on groundwater quality. Global N fertilizer consumption increased from nearly zero in the 1940s to about 80310 Mg N year $^{-1}$ in 1996 (FAO 1997) and up to 87000 in 2004 (Prud'homme, 2005).

The high N input in agroecosystems, particularly with chemical fertilizers and livestock manure, results in large N surplus because frequently exceeds the removal of N via crop products (Velthof et al., 2009). Crop N uptake is not that efficient to ensure small nitrogen losses. Conversely, in European Countries N surplus very often occurs, causing elevate leaching amount, together with volatilization and denitrification losses. Several studies reported observed data showing N surplus in nitrogen balance at field scale ranging from 10 to 250 kg N ha^{-1} year^{-1}, e.g. in Italy (Mantovi et al., 2006; Grignani and Zavattaro, 2000), in Spain (Teira-Esmatges and Flotats, 2003; Dauden et al., 2004), in Denmark (Børsting et al., 2003; Nielsen and Kristensen, 2005), in Netherlands (Fernandez et al., 2002; Fraters et al., 2005) and Germany (Isermeyer and Schleef, 1994; Gömann, 2004). Agricultural management such as crop sequence, fertilization and soil tillage strategy strongly affect leaching losses, especially for N (Aronsson and Stenberg, 2010). N fertilizers use and leaching are closely correlated; the relationship was reported as being exponential by Simmelsgaard and Djurhuus (1998) or as having a break-point

(Lord, 1992) close to application that is consistent with crop N demand. When fertilizer N is applied in amounts exceeding crop N requirements, risk of N leaching increase. More attention should be put on nitrogen use efficiency, defined by Grignani et al. (2003) as the amount of nitrogen applied as fertilizers and manure. The N exceeding crop requirement is potentially subjected to losses, such as volatilization, denitrification and leaching (Di and Cameron, 2002). Nitrate leaching and water contamination have became a major concern in Europe. In order to reduce nitrate pollution from agricultural sources, the European Union Directive 91/676 (EEC) obliges Member States to assess the nitrate concentration and trophic status of their waters thus identifying polluted waters, to designate the territories from which these waters drain as nitrate vulnerable zones (NVZs) and to introduce Action Programmes in these areas. A maximum of 170 kg N $ha^{-1}year^{-1}$ of nitrogen from manure is permitted in nitrate vulnerable zones.

Existing studies reported different values of N application and of N leaching, according to pedoclimatic condition, cropping systems and agricultural management. Morari and Giupponi (1997) reported results of field trials in Po valley (northern Italy) of maize manured according to a fertilization balance, also including a catch crop in rotation in some case. The average amount was 20 to 85 kg N $ha^{-1}year^{-1}$. Mantovi et al. (2006) studied N leaching through the vadose zone in Po valley under silage maize (Zea mays L.) and winter wheat (Triticum aestivum L.) manured by pig slurry combined with mineral N fertilizers. Average annual N leaching was 62 to 186 kg N $ha^{-1}year^{-1}$. N leaching can be calculated by measuring i*n situ* drainage flow and soil solution N concentration with ceramic porous cups (Lord and Shepherd, 1993; Poss er al., 1995; Askegaard et al., 2005) or lysimeters (Prunty and Montgomery, 1991; Thomsen, 2005; Peu et al., 2007). Drainage flow can be simulated by using a simulation model (Askegaard et al., 2005; Gaur et al. 2006). Alternatively, a proper evaluation of nitrogen dynamics can be carried out by applying dynamic simulation models (Acutis et al., 2000; Kersebaum, 2001; Bechini and Stöckle, 2007) .

1.2. Modelling cropping systems and nitrogen dynamics

The importance of simulation models is well recognized (Donatelli et al., 2002) because they are useful tools to organize knowledge and test scientific hypothesis and allowed to explore alternative scenario for agricultural systems management (Fumagalli, 2009). Simulation models can be applied at different application level. There are several simulation model concerning nitrogen dynamics, such as SOILN (Eckersten et al., 1996; Larsson et al.,1999) and LEACHM (Hutson, 2003). All the N-related process are accurately described, but crop variables are not simulated. In order to get a proper evaluation of the nitrogen balance in soil of arable land the analysis of the soil water dynamics and balance has first to be carried out, being water the chief vector of nitrate to groundwater (Rozemeijer et al., 2010; van der Velde et al., 2010). Moreover, a proper evaluation of the soil water content is fundamental in crop yield prediction, since economic production plays a crucial role into an analysis of the actual sustainability of the agroecosystem (Stöckle et al. 1992; Kersebaum, 2007). Together with water and nitrogen balance, an accurate description of crop-related processes has to be part of a simulation model of the crop-soil-atmosphere continuum. Such models can be use to run simulation at cropping or farming system level. Cropping system simulation model are widely widespread, such as CropSyast (Stöckle et al., 2003) HERMES (Kersebaum, 2007), RZWQM (Ahuja et al., 2000), and used in traditional agronomic research. The aim is to evaluate the effects of specific agricultural practices such as, fertilizations, tillage, irrigations, crops rotation on crops productivity and on the environment. (Acutis et al., 2000; Confalonieri et al., 2006). By applying simulation models under different scenarios it is possible to evaluate alternative management in order to maximize crop yield and at the same time minimize N losses.

1.3. Agricultural area in Lombardia plain

In Lombardia designated NVZs represent approximately 67% of the utilised agricultural area (UAA) in Northern Italy. In detail the percentage of NVZs over the UAA exceeds 80% in Lombardia, whereas NVZs represent 56% of the regional plain areas (Regione Lombardia, 2006a). In plain area of the Lombardia, UUA is about 790,000 ha and cropping systems, maize-based, are cereals and forages (Bechini and Castoldi, 2009; Fumagalli, 2009). Such crops have a relative high N requirement and a potential N uptake which allow for elevated N input up to 300 kg ha^{-1}. Farming systems in the plains of the region are strictly linked to livestock type: i) dairy and beef cattle (2,000,000 units) and ii) pig (4,080,000 units) (ISTAT, 2010b). The average nitrogen load from livestock is about 172 kg N ha^{-1}. Such high livestock density involves high availability of N manure but also serious problems related to manure stock and disposal so that nitrate leaching from arable land is a current concern. As consequence of the Nitrates Directive and Italian regulation (Ministero delle politiche agricole e forestali, 2006), a regional action program to reduce nitrate losses was issued by the Lombardia region (Regione Lombardia, 2006a). Fifty-six percent of the total plain regional area (corresponding to 62% of the agricultural area) has been defined vulnerable to nitrates. By the way, in the last years, Lombardia region funded different projects aimed to study and to analyse the nitrate leaching phenomena in order to find potential solutions. ARMOSA project -“Monitoring network of soil water quality of arable land in Lombardia”- dealt with (i) collecting and storing data of monitoring site in Lombardia alluvial plain under intensive cropping systems, (ii) calibration, validation and continuous application of the model ARMOSA, evaluating different agricultural management at field scale to derive sustainable nitrogen managements at regional scale. Based on this project was born and developed my PhD education program.

1.4. Research framework

Nitrate leaching from agricultural production systems is a crucial concern in the intensive agriculture of Lombardia region. Under different pedoclimatic conditions in this region *in situ* monitoring and modelling analysis was defined to evaluate the potential N losses via leaching from arable land by evaluating agricultural management. The research consisted of:

- measuring data of soil, crop, water, and N-related variables at six monitoring fields in farms of Lombardia plain;
- creating a data base of collected data from each site;
- developing the ARMOSA dynamic model able to simulate all the processes involved in cropping systems;
- calibrating and validating ARMOSA model by using the observed data, getting to a proper parameterization;
- applying the ARMOSA model at the entire regional plain, evaluating three different scenarios of cropping systems and management in terms of yield production and N leaching.

1.5. Synopsis

In Chapter 2 *(SWAP, CROPSYST and MACRO comparison in two contrasting soils cropped with maize in northern Italy)* a comparison of three simulation models of soil water balances (SWAP, MACRO and CropSyst) was presented. The objective was to evaluate the performance of three well known models based on the solution of the Richards' equation in two soils of the above-mentioned six monitoring sites. The models were compared on the basis of their reliability to predict soil water content, measured by TDR probes, at 10 depths over two years.

Chapter 3 *(Nitrate leaching under maize cropping systems in Po valley (Italy))* introduces the six monitoring sites which are located in the Lombardia plain. Monitoring procedures of soil water content and soil NO_3-N concentrations along the soil profile are described. The observed data of water and nitrogen allowed to calculate the N losses via leaching in each monitoring sites. An evaluation of the different results highlighted the significant factors involved in N leaching.

Chapter 4 *(The ARMOSA simulation crop model: main features, calibration and validation results)* contains a description of the ARMOSA simulation model. In particular, all the N-related processes are accurately described. The observed data collected in the above-mentioned six monitoring sites allowed to parameterize the model. Procedure and results of calibration and validation procedure are also reported.

Chapter 5 *(Regional application of the ARMOSA model to estimate nitrogen leaching under different agriculture management of intensive cropping systems)* refers to the regional application of the ARMSOA model to evaluate N leaching under different cropping systems and management in three alternative scenarios. The results of model application are presented focusing on the effects of the different crop rotations and management on yield and N leaching.

1.7.Notes

Chapter 2 has been published by Agricultural Water Management journal (vol.97 (2010), pp 1051–1062).

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Chapter 4 has been submitted for publication to Environmental Modelling and Software journal.

Chapter 5 has been submitted for publication to Regional Environmental Change journal.

The reference lists from individual chapters have been combined into one list at the end of the thesis.

Chapter 2

SWAP, CROPSYST and MACRO comparison in two contrasting soils cropped with maize in northern Italy

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Keywords

Hydrological models, Model evaluation, Soil water content, TDR

2.1. Abstract

The quantification of the water balance terms within soil-crop-climate systems is required to derive proper management for plant growth and irrigation. A large number of available models uses the well known Richards' equation for the simulation of water redistribution at field scale. Despite their common basis of the representation of water flow in the unsaturated zone, apparently similar hydrological models give different answers if applied in the same pedological, climatic and agronomic scenarios.

The objective of the present study was evaluating and comparing the performance of three well known models (SWAP, MACRO and CropSyst) based on the solution of the Richards' equation: in a structured fine soil (Calciustepts located in Cerese, Mantova, Italy) and in a structured fine loamy over sandy soil (Hapludalf located in Caviaga, Lodi, Italy), both cropped with maize. The models were compared on the basis of their reliability to predict soil water content, measured by TDR, at 10 depths over two years.

We compared the three models on the basis of difference-based indexes (CRM and RMSE) and correlation statistics (r and EF): at three depths (0-0.15, -0.4 and -1.0 m), in terms of soil water content profile following a drainage process on bare soil and on soil water content over the whole soil profiles.

Although retention and conductivity curves were properly measured in laboratory on undisturbed soil samples, all three models required calibration and validation to obtain good quality simulations. The performances of the three models were quite similar: the average of all (models, sites and depths) root mean square error (RMSE) was 0.032 cm^3 cm^{-3} (±0.007).

Generally, SWAP had the best performance especially in simulating surface infiltration and drying processes, followed by CropSyst and then MACRO.

The better performance of SWAP respect the other two models seemed rely on the hydraulic properties parameterization (van Genuchten-Mualem vs.

Campbell equation), and to the different techniques used for the numerical solutions of Richards' equation close to the bottom and upper boundaries. Moreover, despite its rather good performance, CropSyst, due to its internal numerical constraints in the parameterization of the retention and conductivity functions, needed a very strong calibration then loosing part of its "physical basis" towards an increasing of its empiricism.

2.2. Introduction

The accurate quantification of the water balance and water redistribution in soil is strictly required for a proper simulation of solute transport and for management of plant growth and irrigation.

Nowadays the solution of Richards' equation (Richards, 1931) is the standard approach in water balance modeling in order to deal with infiltration and water redistribution in soil. Several models solving Richards' equation are available (e.g., SWAP, van Dam et al., 1997, Kroes et al. 1998; CropSyst, Stöckle et al., 2003, Stöckle and Nelson, 2005; Hydrus, Šimůnek et al., 2005; RZWQM, Ahuja et al., 2000; MACRO, Larsbo and Jarvis, 2003). Despite their common basis of the representation of water flow in the unsaturated zone, apparently similar hydrological models give different results when applied in the same pedological, climatic and agronomic scenarios (Šimůnek et al., 2003; Vanderborght et al., 2005).

Evaluations of new models are frequently reported in literature (Vanclooster et al., 1995; Kroes et al., 2000; Sheikh and van Loon, 2007; Abraha and Savage, 2008; Suleiman, 2008), whereas few studies are focused on models results comparison. This topic is very important when we have to choose the most suitable model for practical applications in terms of equilibrium between performance and complexity in input requirement (Confalonieri et al., 2009).

Scanlon et al. (2002) compared seven models simulating shallow soil water balance of non-vegetated systems. According to their results, most of the differences between measured and simulated soil water content (SWC) values are due to the water retention curve parameterization, to the time discretization of precipitation input, to the upper boundary condition during precipitation and to the lower boundary condition. Eitzinger et al. (2004) compared SWAP, WOFOST (Supit et al., 1994) and CERES (Ritchie, 1998) models performance in simulating soil water content and crop yields over winter wheat and spring barley cropping season. Parameterization of evapotranspiration and root growth shows to be the most relevant factor affecting models performance. Vanderborght et al. (2005) compared the numerical solution of Richards' and Convection-Dispersion equations for water flow and solute transport, implemented in five models (SWAP; MACRO; HYDRUS; WAVE, Vanclooster et al., 1996; MARTHE, Thiery, 1990) against a set of analytical solutions. Spatial discretization of the pressure head profile close to the soil surface and methods of averaging the hydraulic conductivities show to be the main sources of differences in model results.

Most of these studies are conducted on soils ranging from sandy to loam while few are the scientific contributions on clayey soils.

Our study deals with field measurements and model simulations at two sites in the Po Valley, the largest irrigated area of Northern Italy with mainly loamy and clayey soils. In this area, cropping system models were evaluated by Confalonieri and Bechini (2004) on alfalfa, Acutis et al. (2000) on maize and rye grass, Donatelli et al. (1997) on barley, maize and soybean. Most of these works focused chiefly on yield and other crop features while they devote less attention to soil hydraulic parameterization and water flow. Since crop system modeling is strictly related to soil water balance, then an accurate analysis of soil hydraulic parameters and water flow processes is required to assess model performances.

The aim of the present study is to evaluate and compare the performance of three well known models (SWAP, MACRO and CropSyst based on the solution of the Richards' equation) in terms of simulated soil water contents, using detailed high frequency and high–resolution measured data. In detail, the comparison has been obtained through: (i) the overall evaluation along the profile of the response of the models in two soil types (a clay-loamy Inceptisol and a loamy over sand Alfisol); (ii) the comparison at three soil depths (-0.1, -0.4 and -1 m where some key water flow processes are relevant); (iii) the evaluation of models performance in terms of soil water content profile following a drainage process on bare soil.

2.3. Materials and methods

The section is divided in nine subsections accordingly to three main conceptual sections: "Data and Measurements", "Models description" and "Comparison procedures" as reported in Table 2.1.

Table 2.1. The Materials and Methods section division.

Materials and Methods		
Data and Measurements	Models description	Comparison procedures
Site description	Simulation models	Calibration procedures
Field trials	Soil water flow	Evaluation model performance
Soil hydraulic properties	Water uptake Crop growth parameterization	

2.3.1. Sites description

Experimental data were collected in two sites, Caviaga (45.31°N, 9.50°E, 72 m a.s.l.) in Lodi area and Cerese (45.12°N, 10.79°E, 20 m a.s.l.) in Mantova area, located in the Po Valley (Northern Italy), characterized by intensive crop-livestock system (corn, forage, cattle and pig rearing). The plain consists of a large subsidence basin subjected to complex lowering phenomena and to a gradual infilling by, largely Holocene, sediments derived from the erosion of nearby mountains and then subject to redistribution by alluvial processes.

The soil of Caviaga is a fine loamy over sandy, mixed, superactive, mesic, deep, moderately acid Ultic Hapludalf, widely unsaturated in the exchange complex. The soil of Cerese is a fine, mixed, superactive, mesic Vertic Calciustepts. It is a clay loam soil, characterized by a deep calcic horizon and high content of calcium carbonate with an exchange complex always saturated. A description of the main soils properties of each site is given in Table 2.2. In the Cerese site, despite the high clay content and the occurrence of slickensides (Bss horizon), no evident considerable cracking is detectable in the field; this feature could be related to the irrigation practice and the rather shallow actual groundwater.

The mean annual rainfall over 38 years (1971-2008) is about 752 mm in Cerese and 867 mm in Caviaga. The mean annual temperature in the same period is 13.5 °C in Cerese and 13.0 °C in Caviaga. Such values are related to Mantova and Lodi province observations, respectively (Ucea, 2009).

Table 2.2. Soils properties.

Cerese

Horiz.	Depth (m)	Sand 2000-50 μ	Silt 50-2 μ	Clay < 2 μ	OC g Kg^{-1}	pH (H_2O) -	pH (KCl) -	$CaCO_3$ %	CEC meq 100 g^{-1}
Ap	0-0.4	21.4	44	34.6	10.8	8.1	7	7	22.9
Bss	0.4-0.7	13.6	39.4	47	5.05	8.3	7.1	1	23.7
Bk	0.7-1.3	22.9	50.3	26.8	3.55	8.5	7.6	45	15.1
C	>1.3	88.2	7	4.8	1.75	8.7	8.1	40	1.2

Caviaga

Horiz.	Depth (m)	Sand 2000-50 μ	Silt 50-2 μ	Clay < 2 μ	OC g Kg^{-1}	pH (H_2O) -	pH (KCl) -	$CaCO_3$ %	CEC meq 100 g^{-1}
Ap1	0-0.2	49.5	32.6	17.9	8.15	5.9	5.1	0	15.4
Ap2	0.2-0.3	49.1	33.2	17.7	7.9	6	5	0	12.5
Bt1	0.3-0.6	46.8	31.4	21.8	4.4	6.2	4.7	0	12.2
Bt2	0.6-0.8	74.5	12.1	13.4	1.6	6.7	5.2	0	7.9
BC	> 0.8	83.7	6.3	10	1.1	6.8	5.3	0	7.2

2.3.2. Field trials

Over the 2-years experiment (2002-2003) silage maize was cropped in 2002 and 2003 in the Cerese site and in 2002 in the Caviaga site. In this site maize for grain was cropped in 2003. It was sown at the end of March and harvested in late August. Soil water content was determined in both sites by Time Domain Reflectometry technique (TDR), applying the empirical Topp's formula to the measured soil bulk dielectric permittivity (Robinson et al., 2003). Twelve probes were installed: (i) two, vertically at depth of 0-0.15 m, one within-row and another between-row; (ii) eight, horizontally at 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 m; and (iii) two, vertically at 0.9-1.1 m and 1.1-1.3 m below soil surface. The probes set-up was replicated three times, at a distance of approximately 10 m. In 2002 we got 720 measurements of water content at Cerese site and 291 at Caviaga site, and in the year 2003 we get 1036 and 1266 water content measurements in Cerese and Caviaga site, respectively. Pressure head was measured by tensiometers installed at 1.1, 1.3, 1.4 m below soil surface in three replicates located close to the TDR probes. The TDR probes were connected by a 36-channels multiplexer to a cable tester Tektronix 1502/C. Soil water contents were measured every four hours. In the following of this paper the daily average SWC will be used. For tensiometer readings, pressure transducers were connected to a 16-channels multiplexer (A16/32, Campbell Instrument Inc) and the pressure head measured each two hours.

The five probes installed from the surface till a depth of 0.4 m were removed at the end of the first maize growing season to avoid damage by the autumn plowing and successive harrowing practices, and reinstalled at the crop emergence of the second maize growing season. Daily meteorological data (rainfall, maximum and minimum air temperature, maximum and minimum relative humidity, wind direction/speed and global solar radiation) were collected by an automatic weather station placed near the experimental fields.

The reference evapotranspiration, ET_0, was calculated by Penman-Monteith equation (Monteith, 1965). Water table depth was weekly or bi-weekly measured by piezometric pipes installed in the field.

Cerese site was subject to ordinary tillage practices (plough up to 0.4 m) while in the Caviaga site minimum tillage at 0.15 m of depth has been carried out since 15 years, producing Ap1 and Ap2 layering. Irrigation water was delivered by big guns in the Cerese site and by border in the Caviaga site.

Crop phenology was recorded weekly; LAI (Leaf Area Index) was estimated by LAI2000 instrument (Welles, 1990) at three development stages (flowering, milk maturity and harvesting). Above ground biomass was measured at flowering and at harvesting.

2.3.3. Soil hydraulic properties

Undisturbed soil samples of each horizon (ϕ=86 mm, h=130 mm) were collected. In the laboratory the samples were saturated from the bottom in order to measure saturated hydraulic conductivity by a falling head permeameter (Reynolds and Elrick, 2002). The experimental relationship between soil water content and pressure head (namely, water retention curve, $\theta(h)$) and between soil water content and hydraulic conductivity (namely, hydraulic conductivity curve, $K(\theta)$) were determined according to the Wind's method (Tamari et al., 1993; Arya, 2002) during an evaporation process; four supplementary points – at -10, -40, -80 and -150 m - of the water retention curve were determined by means of the pressure plate apparatus (Dane and Hopmans, 2002). The unsaturated hydraulic conductivity curve was obtained by the algorithm suggested by Watson (1966), according to Kutilek and Nielsen

(1994). From tensiometers readings and water retention curve, water contents θ (z, t) allow calculation of the water stored W at time t in the soil sample compartment between soil sample surface and depth z. The average flux density during a time interval $\Delta t = t_2 - t_1$ is $\bar{q}(t) = -\Delta W/\Delta t$, ΔW being the water loss from the soil compartment (0, z). Substituting the average flux density in the finite difference form of the Darcy equation, $\bar{q} = -K(\bar{\theta})\Delta H/\Delta z$, yields:

$$k(\bar{\theta}) = -\frac{\Delta W}{\Delta t} \bigg/ \frac{\Delta H}{\Delta z} \qquad [2.1]$$

where the gradients of the total potential head, $H(=h+z)$, are calculated from $h(z, t)$ measurements and $\bar{\theta}$ is related to the mean $\bar{h}$ of Δh in ΔH.

For the only sample Bt1 of the Caviaga site, the $\theta(h)$ data points were measured using conventional suction table and pressure plate apparatus (Dane and Hopmans, 2002). Water retentions were obtained at the following pressure heads: -0.01, -0.03, -0.06, -0.09, -0.15, -0.26, -0.53, -0.93, -1.63 m by means of tension table and at 10, 40, 80 and 150 m by means of pressure plate.

2.3.4. Simulation models

Three models were selected to evaluate their performances in simulating soil water balance, SWAP ver. 2.07 (Van Dam et al., 1997; Kroes et al., 1998), MACRO ver. 5.1 (Larsbo and Jarvis, 2003) and CropSyst ver. 3.04 (Stöckle et al., 2003, Stöckle and Nelson, 2005). These models were selected because (i) they are well tested and widely applied in different agro-hydrological scenarios, both worldwide and in the area of study, (ii) they have a strong physical basis, the one-dimensional Richards' equation.

A concise models description follows; more emphasis on their differences is reported. Details can be found in the specific references of each model. Main differences are related to the numerical solution of the Richards' equation, the hydraulic properties parameterization, the water uptake schematization and the crop growth description.

2.3.4.1. Soil water flow

The three models calculates the soil water flow solving the Richards' equation for soil water flow in the soil matrix by an implicit finite difference scheme:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S(h) \qquad [2.2]$$

where θ (cm^3 cm^{-3}) is the volumetric soil water content, h (cm) is the soil water pressure head, t (d) is the time, z (cm) is the vertical coordinate taken positively upward, K (cm d^{-1}) is the hydraulic conductivity and S (cm^3 cm^{-3} d^{-1}) is the water extraction rate by the plant roots.

The time discretization is an explicit linearization of conductivity in SWAP and MACRO, but not documented in CropSyst; being the pressure head calculated, the hydraulic conductivity is the average of the conductivities in the adjacent nodes: the arithmetic mean is used in SWAP and the geometric mean in MACRO (not yet documented in CropSyst).

Soil water retention is described for SWAP and MACRO by the unimodal θ (h) relationship proposed by van Genuchten (1980) and expressed here in terms of the effective saturation, Se, as follows:

$$Se = \left[\frac{1}{1+\left(\alpha\,|h|\right)^{n}}\right]^{m} \qquad [2.3]$$

with $Se=(\theta-\theta_r)/(\theta_0-\theta_r)$, θ_r and θ_0 being the residual water content and the water content at h=0, respectively, and in which α (cm^{-1}), n and m are curve-fitting parameters.

Mualem's expression is applied to calculate relative hydraulic conductivity, K_r, (Mualem, 1976).

Assuming m=1-1/n, van Genuchten (1980) obtained a closed-form analytical solution to predict K_r at a specified volumetric water content:

$$K_r(Se) = \frac{K(Se)}{K_0} = Se^{\tau}\left[1-\left(1-Se^{1/m}\right)^m\right]^2 \qquad [2.4]$$

in which K_0 is the hydraulic conductivity measured at θ_0, and τ is a parameter which accounts for the dependence of the tortuosity.

While SWAP and CropSyst are one-region models, MACRO is a two-regions model where the total soil porosity is partitioned into two flow regions, micropores and macropores. In the latter region, capillarity is assumed to be negligible so that water flow is dominated by gravity ($\partial h/\partial z=0$). The governing equation for water flow in macropores is:

$$\frac{\partial \theta_{ma}}{\partial t} = \frac{\partial K_{ma}}{\partial z} - \sum S_i \qquad [2.5]$$

where θ_{ma} and K_{ma} are the macropore water content and hydraulic conductivity, respectively. This approach in describing water flow in the macropores is equivalent to the kinematic wave approach described by Germann (1985).

In CropSyst the soil hydraulic functions are described by the analytical expressions of Campbell (1985). The soil water retention function is:

$$\begin{aligned} h &= h_b && \text{for} \quad h \geq h_b \\ h &= h_b \cdot (\theta / \theta_0)^{-\lambda} && \text{for} \quad h < h_b \end{aligned} \qquad [2.6]$$

where h_b is the air entry water potential (potential at which the largest water filled pores just drain), and λ is the slope of ln$h$ vs lnθ. The hydraulic conductivity is described by:

$$K(h) = K_0\left(\frac{h_b}{h}\right)^{2+\frac{3}{\lambda}} \qquad [2.7]$$

The condition at the bottom boundary can be set in several ways (i.e. pressure head, water table, fluxes, impermeable layer, unit gradient, etc…). For all the tested models the setting of the unit gradient at the bottom of the Caviaga site soil profile and the measured water table depth at the Cerese site have been carried out.

2.3.4.2. Water uptake

SWAP simulates water uptake and actual transpiration according to the model proposed by Feddes et al. (1979), where root water uptake *S* is described as a function of the pressure head, *h*:

$$S(h) = \alpha(h) S_{\max} = \alpha(h) {}^{T_p}\!/_{z_r} \qquad [2.8]$$

being z_r (cm) the thickness of the root zone and $\alpha(h)$ a semi-empirical function of pressure head *h*, varying between 0 and 1. The shape of the function $\alpha(h)$ depends on four critical values of *h*, which are related to crop type and to potential transpiration rates. The actual transpiration rate T_a (cm d^{-1}) is computed by the integration of *S* over the root layer. If simple crop model is chosen the root depth is specified by the user as function of development stage.

In MACRO root water uptake is calculated as in SWAP model. The ratio between actual and potential root water uptake (T_a/T_p) is assumed to be a function of a dimensionless water stress index ω^*:

$$\omega^* = \sum_{i=l}^{i=k} r_i \cdot \omega_i \qquad [2.9]$$

where *k* is the number of soil layers in the profile containing roots and r_i is the proportion of the total root length. ω_i is a threshold-type empirical function of the soil water content described by Jarvis (1989) and depending on four characteristic soil water contents. The water uptake sink (S) is therefore computed by:

$$S = \left(\frac{T_a}{\Delta z_i} \right) \cdot \left(\frac{r_i \cdot \omega_i}{\omega^*} \right) \qquad [2.10]$$

where Δz_i is the thickness (cm) depth below the soil surface of layer *i*.

Computed water uptake is generally water from macropores. Moreover, when water stress exceeds a critical value of water stress index ω_c* (the 'root adaptability factor') which involves transpiration reduction, the crop deals with the stress by increasing uptake from wetter layers where conditions are more favorable (Jarvis, 1989). Any excess demand is then satisfied from water stored in the micropores.

In CropSyst model each layer water uptake is calculated as a function of (i) the difference between soil and xylem water potential, (ii) root conductance (Stöckle et al., 1992). The soil conductance is assumed to be higher than root conductance so that water uptake is not limited by water movement towards the roots. The water uptake, WU_i (kg m^{-2} day^{-1}), from each soil layer *i* is given by:

$$WU_i = 86400 \, \frac{C_i}{1.5} \left(\psi_{s\_i} - \psi_l \right) \qquad [2.11]$$

where ψ_{s_i} (J kg^{-1}) is the soil water potential of soil layer *i* (Campbell, 1985), ψ_{sl} (J kg^{-1}) is the leaf water potential, C_i (kg s m^{-4}) is the roots conductance of soil layer *i,* 86400 is the number of seconds per day and 1.5 is a factor that converts total root conductance to total plant hydraulic conductance. The total water uptake *WU* is the sum of the water uptake from each soil layer.

2.3.4.3. Crop growth parameterization

Crop growth can be simulated in SWAP by the code of WOFOST (Hijmans et al., 1994) as a function of the radiation energy absorbed by the canopy and photosynthetic leaf characteristics energy or using a simplified approach based on a simple crop growth model in which the user specifies the leaf area index (m^2/m^2, LAI), the crop coefficient (K_C) and rooting depth as function of development stage (DVS). In this work we have used the latter approach.

In the MACRO model the crop growth is basically described by a simple crop model as in SWAP. However, the LAI and the root development follows a logistic curve, parameterized by the user.

In CropSyst model the crop growth is simulated for the whole canopy by calculating unstressed biomass growth as the minimum of two values of daily aboveground biomass rate. In fact, such rate is calculated as function of potential transpiration and of intercepted radiation. Unstressed biomass growth value is then corrected by water and nitrogen limitations to simulate actual daily biomass accumulation. The root growth is synchronized with leaf area growth (Stöckle et al., 2003). The water stress reduces biomass accumulation (and consequently LAI and roots development) proportionally to the actual to potential evapotranspiration ratio. The maximum value of root depth is given as input by the user and the root density is assumed to decrease linearly with depth (Campbell and Diaz, 1988) with a maximum at the top of the soil profile and a value of zero at the tip of the current root depth. All the three models were calibrated to obtain the closest possible simulation of LAI and biomass values in both years.

The time course of the Leaf Area Index (LAI) is a key state variable for the three models, controlling crop growth and the partition of the evapotranspiration in evaporation and transpiration. Thus, we have calibrated the detailed crop model implemented in CropSyst against some LAI, biomass production and nitrate measurements taken in 2003, 2004 and 2005 in both experimental sites. Then, the calibrated LAI function is employed in SWAP and MACRO. In such a way, in a no N stress condition, the differences between the three models in terms of crop parameterization are reduced to the minimum, enlightening the differences due to the water flow schematization.

2.3.5. Calibration procedure

The basic aim of the calibration is to improve the parameters estimation (Jörgensen, 1994) by their adjustment within a reasonable range as indicated by previous research, knowledge or experience.

Several parameters for each of the three tested models were adjusted according to the trial-and-error procedure (Table 2.3). Two categories of parameters were mainly involved in the calibration: (i) relevant parameters of the water uptake/transpiration processes and (ii) few parameters concerning the hydraulic properties parameterization. Water uptake calibration requirement was due to the lack of detailed observed data of this process. We first calibrated the transpiration process of CropSyst using measured yield and LAI data in the calibration procedure to get a reliable crop growth and transpiration simulation. Then we tried to some extent to get similar outputs of transpiration in SWAP by the calibration of the root depth and the root density distribution and in MACRO by adjusting the *root adaptability factor*.

Concerning hydraulic properties, to get a reliable soil water balance, it is crucial a proper parameterization. Due to the hysteresis in water retention curve, laboratory-based soil hydraulic characterization carried out on undisturbed cores does not reproduce properly the *in situ* soil hydraulic behavior (Kutilek and Nielsen, 1994). In such a way a lower value of the maximum soil water content is observed. This soil water content, referred at $h=0$, is often defined “satiated” (Hillel, 1980). Basile et al. (2003, 2006) demonstrated that also the saturated hydraulic conductivity and, only slightly, the air bubble value are modified with respect to values observed under field conditions. Therefore, we calibrated the models trying to adjusting mainly the parameters θ_0 and K_0 (Eqs. 2.2., 2.3., 2.6. and 2.7.).

2.3.6. Evaluation of model performance

The agreement between observed and predicted values was expressed by the indexes proposed by Loague and Green (1991) and more recently discussed by Martorana and Bellocchi (1999) and Fila et al. (2003): the root mean squared error RMSE, the coefficient of residual mass CRM and the Pearson correlation *r*. For all the indexes O_i is the *ith* measured value, S_i is the estimated *ith* value and *n* is the number of soil water content pairs. $\overline{O}$ and $\overline{S}$ are the mean of observed and simulated soil water content, respectively.

The root mean square error RMSE has a minimum and optimum value at 0. It is a difference-based measure of the model performance in a quadratic form, and it is fairly sensitive to outliers:

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}(O_i-S_i)^2}{n}} \qquad [2.12]$$

The coefficient of residual mass, CRM, ranges between -inf and +inf, with the optimum=0. If positive it indicates that the model underestimates the prediction, if negative indicates overestimation and when is close to zero indicates the absence of trends:

$$CRM = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} O_i} \qquad [2.13]$$

The coefficient of correlation *r* (Addiscott and Whitmore, 1987) has its optimum value to maximum (+1) values. Zero means no correlation:

$$r = \frac{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)\left(S_i - \bar{S}\right)}{\sqrt{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)^2} \sqrt{\sum_{i=1}^{n} \left(S_i - \bar{S}\right)^2}} \qquad [2.14]$$

Modeling Efficiency (EF) (Greenwood et al., 1985) can get either positive or negative values, 1 being the upper limit, while negative infinity is the theoretical lower bound. EF values lower than 0 result from a worse fit than the average of measurements

$$EF = \frac{\sum_{i=1}^{n} (O_i - \bar{O})^2 - \sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \qquad [2.15]$$

2.4. Results and discussion

In this section, details will be given as follows:

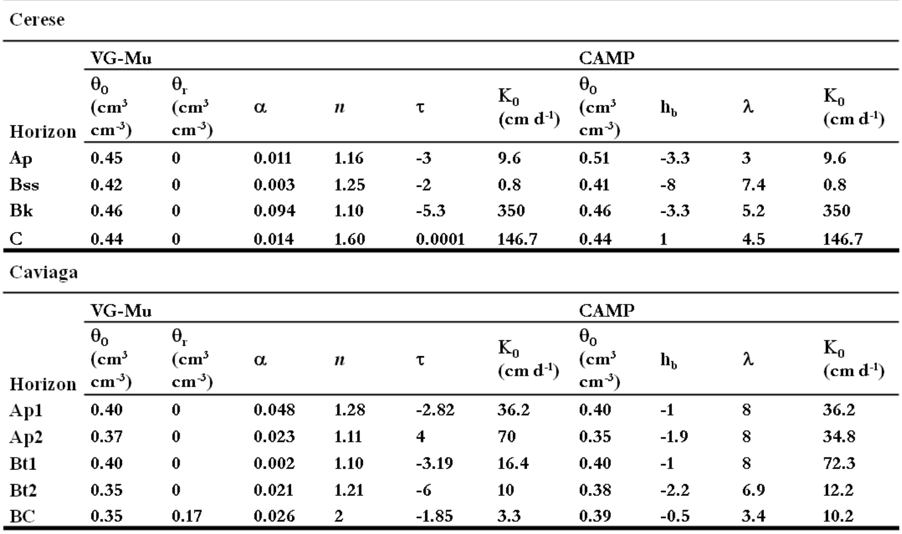
i) main results of model’s input parameters dealing with soil hydraulic properties and upper and lower boundary conditions; ii) evaluation of models performance at three depths: 0-0.15, -0.4 and -1.0 m. They were selected, among the 10 investigated depths, being representative of depths where some key water flow processes are relevant (infiltration and evaporation at surface, water uptake at -0.4 m and drainage at -1.0 m); iii) evaluation of models performance in terms of soil water content profile following a drainage process on bare soil and iv) overall evaluation and models comparison in terms of estimated and simulated soil water content over the whole soil profiles.

2.4.1. Main results on relevant model's input parameters

2.4.1.1. Soil hydraulic properties

The VG equation for the water retention (Eq. 2.3) shows for all the horizons high values of R^2 (>0.96) both for Cerese and Caviaga site. On the contrary, the CAMP relationship (Eq. 2.7) gives generally lower values (average $R^2 = 0.91$), with the exception of the deeper horizon of Cerese where the coefficient of determination rises up to 0.99. These results are mainly due to: (i) the greater adaptability to measured data of the VG model respect to CAMP one (among others, Van Genuchten and Nielsen, 1985); (ii) the constraints of the CropSyst model (reported in the Material and Methods section) that reduce the capability of the CAMP model to properly follow experimental data. The experimental hydraulic conductivity data are accurately fitted by the VG-Mu model in all horizons of both sites (average R^2 is 0.93, and the worst R^2 is 0.83). CAMP model gives excellent results in the fitting of the hydraulic conductivity data with an average value of R^2 of 0.92. Similar results for both water retention and hydraulic conductivity were found in literature. For instance, Yates et al. (1992) analyze the results of 36 soil samples. They show an average R^2 value of 0.988 applying the 4-parameters van Genuchten relationship (Eq. 2.3), without setting constraints to the n and θ_r parameter value. Furthermore, their comparison between measured and estimated log10 transformed hydraulic conductivity get several R^2 values with high variability (ranging between 0.31 and 0.97) and with an average value lower than our average of 0.93. The results, in terms of coefficient of determination, are sufficiently reliable when compared to those found in literature even for CAMP retention and conductivity functions that show values not as good as VG-Mu model. The parameters applied in the model simulations are shown in Table 2.3. According to the parameters, Cerese site shows a fairly homogeneity of the water retention curves of the upper horizons (Ap and Bss). A lower value of K_0 is shown by the Bss horizon, which is less permeable than the upper one. A discontinuity in hydraulic property is shown by the Bk horizon (namely, lower n and higher K_0) and at the bottom of the profile where the C horizon shows hydraulic parameters in agreement with the coarser texture (Table 2.2). Caviaga site profile seems to be homogeneous till the BC horizon that shows a higher n, according to its coarser texture. A slight decrease of the K_0 is also shown in Table 2.3 as soil depth increases.

Table 2.3. Soil hydraulic parameters.



Cerese

	VG-Mu						**CAMP**			
Horizon	**θ_0 (cm³ cm⁻³)**	**θ_r (cm³ cm⁻³)**	**α**	**n**	**τ**	**K_0 (cm d⁻¹)**	**θ_0 (cm³ cm⁻³)**	**h_b**	**λ**	**K_0 (cm d⁻¹)**
Ap	**0.45**	**0**	**0.011**	**1.16**	**-3**	**9.6**	**0.51**	**-3.3**	**3**	**9.6**
Bss	**0.42**	**0**	**0.003**	**1.25**	**-2**	**0.8**	**0.41**	**-8**	**7.4**	**0.8**
Bk	**0.46**	**0**	**0.094**	**1.10**	**-5.3**	**350**	**0.46**	**-3.3**	**5.2**	**350**
C	**0.44**	**0**	**0.014**	**1.60**	**0.0001**	**146.7**	**0.44**	**1**	**4.5**	**146.7**

Caviaga

	VG-Mu						**CAMP**			
Horizon	**θ_0 (cm³ cm⁻³)**	**θ_r (cm³ cm⁻³)**	**α**	**n**	**τ**	**K_0 (cm d⁻¹)**	**θ_0 (cm³ cm⁻³)**	**h_b**	**λ**	**K_0 (cm d⁻¹)**
Ap1	**0.40**	**0**	**0.048**	**1.28**	**-2.82**	**36.2**	**0.40**	**-1**	**8**	**36.2**
Ap2	**0.37**	**0**	**0.023**	**1.11**	**4**	**70**	**0.35**	**-1.9**	**8**	**34.8**
Bt1	**0.40**	**0**	**0.002**	**1.10**	**-3.19**	**16.4**	**0.40**	**-1**	**8**	**72.3**
Bt2	**0.35**	**0**	**0.021**	**1.21**	**-6**	**10**	**0.38**	**-2.2**	**6.9**	**12.2**
BC	**0.35**	**0.17**	**0.026**	**2**	**-1.85**	**3.3**	**0.39**	**-0.5**	**3.4**	**10.2**

For both the investigated soils, the coefficients of determination for retention and conductivity functions are reported in Table 2.4.

Table 2.4. Coefficients of determination, R^2, of the fitting procedure of the Eq. 2.3 (water retention), Eq. 2.4 (hydraulic conductivity) for van Genuchten and Mualem model (VG-Mu) and Eq. 2.6 (water retention), Eq. 2.7 (hydraulic conductivity) for model (CAMP).

Cerese

	VG-Mu		CAMP	
	Water retention	Hydraulic conductivity	Water retention	Hydraulic conductivity
Ap	0.98	0.89	0.92	0.88
Bss	0.96	0.97	0.83	0.89
Bk	0.97	0.98	0.91	0.96
C	0.98	0.99	0.99	0.98

Caviaga

	VG-Mu		CAMP	
	Water retention	Hydraulic conductivity	Water retention	Hydraulic conductivity
Ap1	0.96	0.93	0.94	0.92
Ap2	0.99	0.93	0.83	0.88
Bt1	0.99	--	0.92	--
Bt2	0.97	0.83	0.96	0.76
BC	0.98	0.93	0.96	0.91

2.4.1.2. Bottom and upper boundary conditions

The Cerese site shows a fluctuating shallow water table (Fig 2.1a) whose effects are confirmed by the pressure head values measured by deep tensiometers (data not shown). Reference evapotranspiration, ET_0, and water supply (cumulative rain and irrigations) in 2002 and 2003 are shown both for the site of Cerese (Fig. 2.1a) and Caviaga (Fig. 2.1b) where shallow water table was absent.

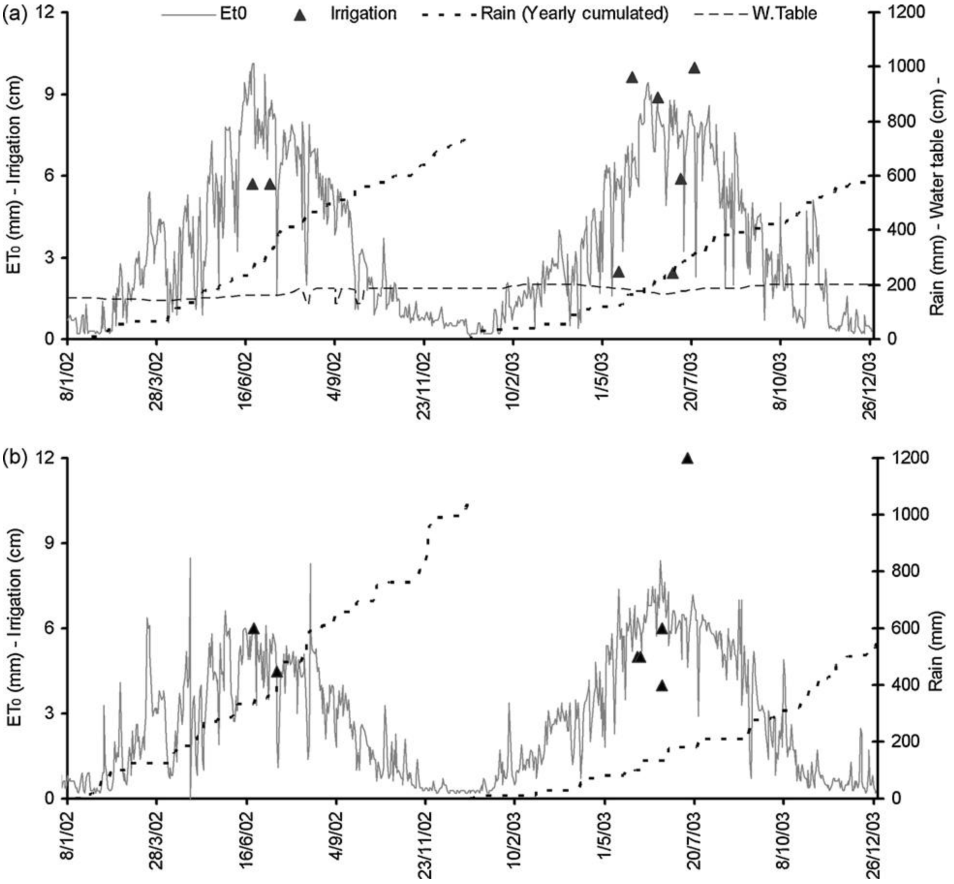


Figure 2.1a,b. Upper boundary conditions of Cerese (a) and Caviaga (b) site for year 2002 and 2003. On the left axes are shown the reference evapotranspiration ET0 (solid line) and irrigations (triangles). On the right axes cumulative rain is shown (dashed line). Moreover, for Cerese site (a) the water table (dotted line) is also shown.

Rainwater amount had different trends in 2002 and 2003: 748 mm and 1049 mm of rain in Cerese and Caviaga in 2002, and 606 mm and 683 mm of rain in Cerese and Caviaga in 2003 (being 752 mm in Cerese and 867 mm in Caviaga the long-term mean values of rain). Also the temperatures follow the same pattern, being the 2002 and 2003, both for Cerese and Caviaga, respectively a relatively cold and hot year. The mean annual temperature was 14.7 °C and 13.7 °C during the 2002 for Cerese and Caviaga, respectively and 15.8 °C and 14.2°C during the 2003. Accordingly, the cumulated reference evapotranspiration was lower in the 2002 than in the 2003 (901 mm vs. 1124 mm for the Caviaga site and 1222 vs. 1288 for the Cerese site).

2.4.2.Simulation at three depths

Figure 2 shows the daily patterns of the soil water content measured and estimated in the Cerese site by the three models in the 2002 at three different depths (0-0.15, -0.4, and -1.0 m). The absolute error ΔE=Ei-Mi of the prediction and rain date are also reported. Different processes are relevant at the considered depths: infiltration and evaporation occur only at 0-0.15 m, water uptake at -0.4 m and drainage at -1.0 m. The range and dynamic of the observed soil water content values are coherent with the three models outputs at each depths. Differences between simulated and measured soil water content decrease through soil profile.

At the surface (0-0.15 m) the three models show a moderate underestimation, larger in MACRO; CropSyst has better performances in terms of RMSE , r and EF, followed by SWAP and MACRO models (Table 2.5).

Table 2.5. Main performance indexes of the three models in Cerese and Caviaga at three soil depths (0-0.15, 0.4,).

		Cerese			Caviaga		
Indexes	**Depth (m)**	**SWAP**	**CropSyst**	**MACRO**	**SWAP**	**CropSyst**	**MACRO**
CRM	0-0.15	0.034	0.035	0.072	-0.070	-0.320	0.186
	0.4	-0.050	-0.033	-0.043	0.040	0.046	-0.063
	1.0	0.002	0.001	0.025	-0.010	0.130	0.062
RMSE (cm^3 cm^{-3})	0-0.15	0.052	0.041	0.059	0.052	0.082	0.066
	0.4	0.031	0.026	0.031	0.029	0.026	0.028
	1.0	0.011	0.014	0.019	0.017	0.029	0.020
R	0-0.15	0.595	0.807	0.534	0.846	0.809	0.789
	0.4	0.625	0.714	0.57	0.760	0.719	0.835
	1.0	0.894	0.791	0.724	0.435	0.663	0.521
EF	0-0.15	0.299	0.574	0.152	0.565	0.174	0.416
	0.4	0.260	0.236	-0.010	0.127	0.105	-0.389
	1.0	0.790	0.773	0.673	0.105	-0.331	-0.576

At -0.4 m depth the three models overestimate the measurements (CRM, in average of the three model of - 0.042); all the models improve the performance in terms of RMSE. In terms of EF, values are worst than those shown in the upper horizon while r remain substantially unchanged for SWAP and MACRO and it is lower for CropSyst. Summarizing, at this depth CropSyst over perform the other models, whereas MACRO has a bad performance.

At -1.0 m SWAP gets the best performance in terms of RMSE, r and EF. CropSyst shows the better value of CRM, while MACRO shows the more unfavorable values for all indexes.

Similarly to Figure 2.2, Figure 2.3 shows coherence between measured and estimated SWC profiles in the Caviaga site. With respect to Cerese application, performance models are contradictory (Table 2.5). At 0-0.15 m depth SWAP overestimates the measurements showing the best performance in terms of CRM, while CropSyst and MACRO show a relevant worsening of the performances, overestimating and underestimating respectively the measurements. Regarding the RMSE the models are ranked from best to worst as follow: SWAP-MACRO-CropSyst. The correlations are rather high and similar (close to 0.8) for all the models (Table 2.5). EF is higher in SWAP, followed by MACRO and CropSyst. At -0.40 m depth models outputs are better than in the upper horizon in terms of the difference-based indexes but it gives worst results in terms of EF and r. MACRO shows a negative value of EF, even if this model have the best value of r.

At the deeper depth of -1.0 m, estimated soil water contents by SWAP almost overlap measurements (CRM=-0.010, RMSE=0.017 cm^3cm^{-3}) and is the only model with a positive value of EF. CropSyst underestimates the measurements and shows higher CRM and RMSE respect the other two models, while MACRO shows the worst value of EF, largely negative. At this depth, for all models, the correlation index r is lower than those showed in the upper layers.

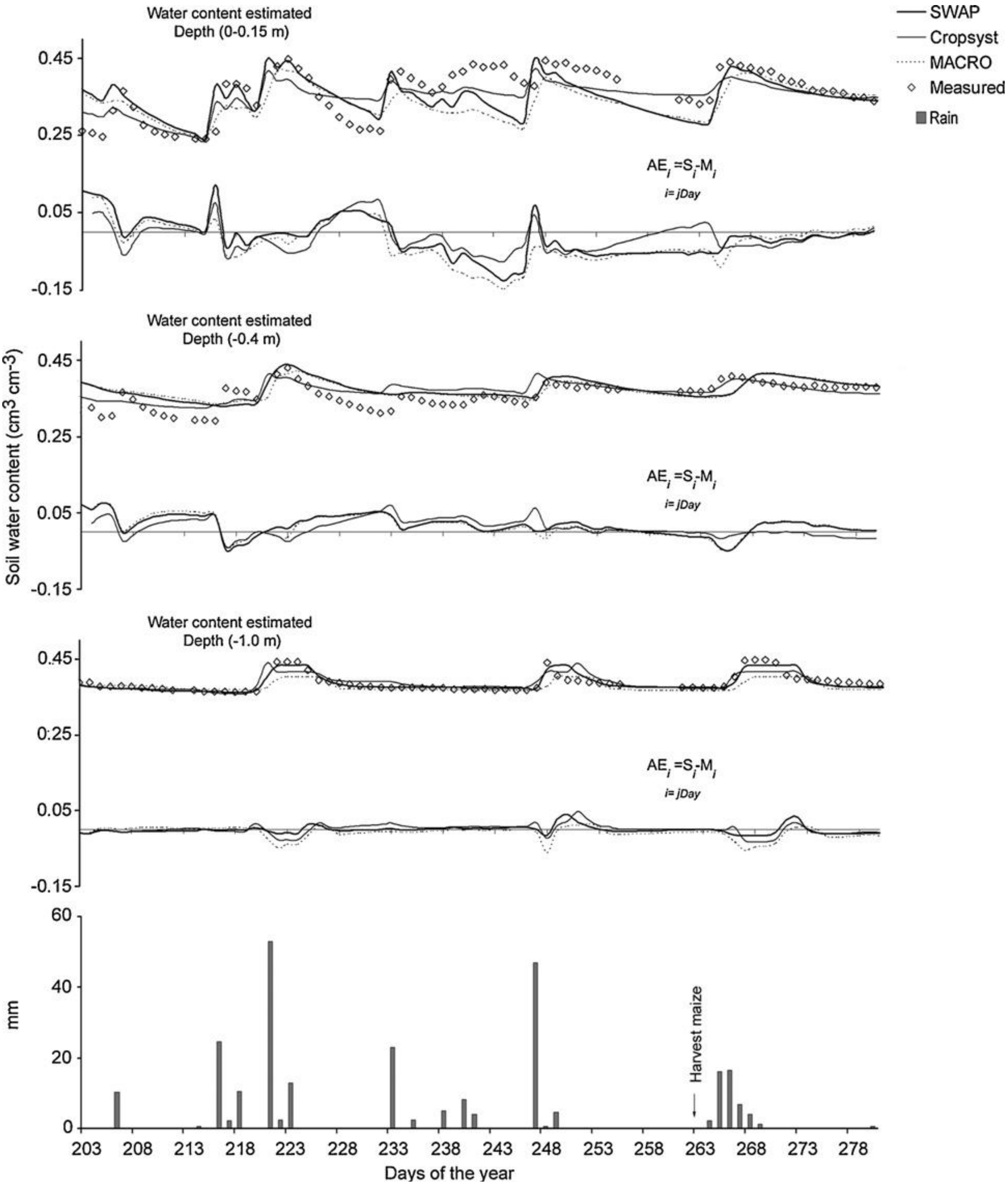


Figure 2.2 Measured (empty circle) and simulated by SWAP (solid line) CropSyst (dotted line) and MACRO (dotted line) soil water content at Cerese. Daily absolute errors (Δ*E*) of the predictions have been reported. Rain and main crop date have been also reported.

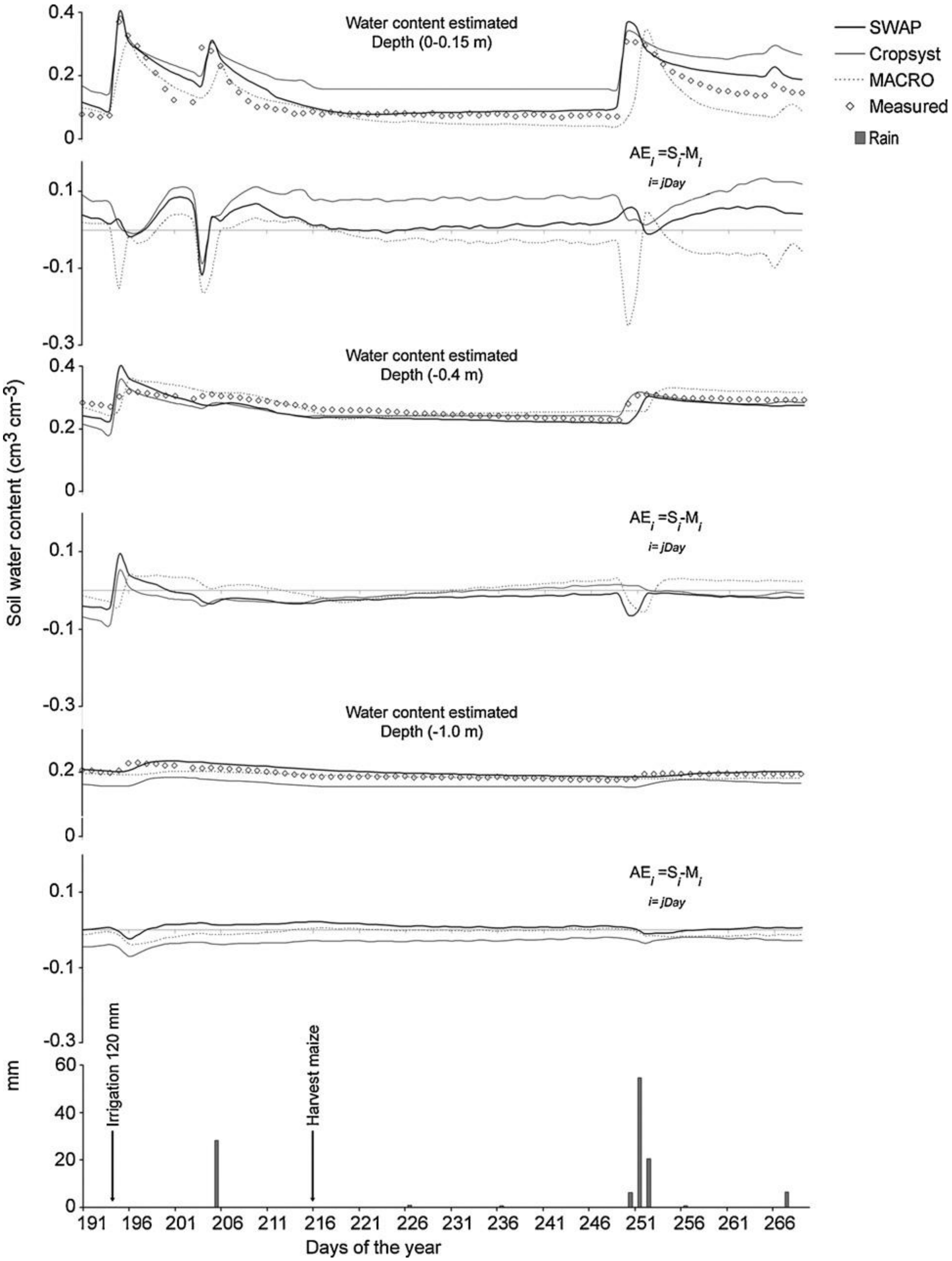


Figure 2.3. Measured (empty circle) and simulated by SWAP (solid line) CropSyst (dotted line) and MACRO (dotted line) soil water content at Caviaga. Absolute errors (ΔE) of the predictions have been reported. Rain and main crop date have been also reported.

2.4.3.Simulation of water content profile on bare soils

In order to discriminate between the models performance in absence of crops, further analyses have been carried out, on both sites, following a simple soil drying process. The evolution of the soil water content profiles on bare soils have been monitored and simulated over 11 days in 2002 in Cerese and over 16 days in 2003 in Caviaga. First day of the comparison analysis has chosen to be the next day after strong rain events in order to start simulations in a quasi-saturated soil initial conditions.

In Fig. 2.4a measured (triangle) and simulated (continuous line) soil water content in Cerese site are shown. The 0-0.15 m soil water contents are reported by vertical bars. Three days of the 11-days drying process (DOY 269 when the process starts, DOY 272 as intermediate value and DOY 279 at the end of the drying period) are reported as the most representative. The DOY 269 at the beginning of the analysis shows a rather homogeneous soil water content profile being the data in the interval 0.39-0.45 (cm^3 cm^{-3}).

In the Ap horizon, at 0-0.15 m the soil gets drier from 0.42 to 0.35 cm^3 cm^{-3} that is due to evaporation process while at -0.2 m and -0.4 m a slight changing is detected in soil water content, indicating a quasi-static (stationary) condition. Taking into account the different starting points of the models, each model gives coherent outputs.

The Bss horizon shows a reduced water dynamic with soil water contents practically unchanged during the tested 11 days. Such behaviour can be ascribed to the low permeability of this type of horizon with respect to both the upper Ap and the lower Bk horizons. The models simulations are very similar and consistent with the measured data. The Bk horizon at the beginning of the test, from the DOY 269 to the DOY 272, shows a fast drainage process: the soil water content at all the measurement depths (-0.8, -0.9, -1.0 and -1.2 m) shows a sharp decrease, on average, of about 0.06 cm^3 cm^{-3}. SWAP gets best results in simulating the variation of soil water content at these depths, both in terms of absolute values and time variations.

In Fig. 2.4b, measured (triangle and vertical bar for 0-0.15 m depth) and simulated (continuous line) SWC profiles in Caviaga site are reported in three days of the 16-days drying process. Such process starts on DOY 251 and ends on DOY 266. On DOY 258 a SWC profile is also shown: the maximum values (θ=~0.30 cm^3 cm^{-3}) are shown at 0-0.15 and -0.5 m depth with decreasing trends towards -0.2 and -1.0 m. Such water content profile is consistent with the absence of water table close to the bottom of the profile. In this 16-days period the upper TDR probe at 0-0.15 m is the only ones that shows a considerable reduction in the water content, namely from 0.31 to 0.14 cm^3cm^{-3}. Only SWAP model simulated correctly this reduction while MACRO overestimate the drying process and CropSyst underestimate it. At the other depths the reduction of SWC in time is very limited (~ 0.02 cm^3 cm^{-3}), but well simulated by all the models.

In both sites CropSyst fails in simulating at 0-0.15 m depth, drying excessively the upper soil strata with an abrupt change of slope between -0.05 and -0.1 m. Such error should be attributed to numerical error occurred in the code, due to the schematization of the soil profile close to the surface. Van Dam and Feddes (2000) showed that, both for infiltration and evaporation, the effects of the nodal distance is crucial to properly simulate the near-surface fluxes, also in reducing the influence of the averaging procedure applied for the hydraulic conductivity. They demonstrated that using a small nodal distance of 1 cm or less yielded soil water fluxes that were very close to the theoretical fluxes respect thicker nodal distances (i.e. 5 cm). SWAP and MACRO allow the user to specify all the nodal distances while, CropSyst automatically divides the thickness of the horizons in sub-layers (nodal distances) of 5 cm (at surface) or 10 cm (at major depth).

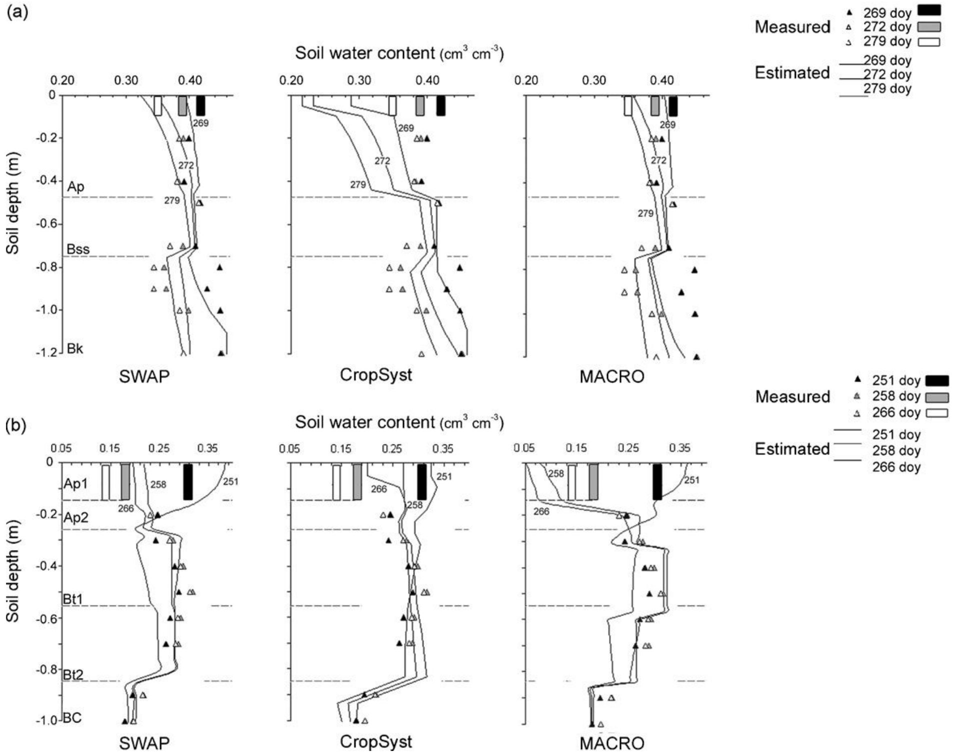


Figure 2.4. Measured (triangle) and simulated by the three models (continuous line) SWC profiles on bare soil in Cerese site in 2002 (a) and in Caviaga in 2003 (b) in three days of the year (doy). Vertical bars shown the 0-0.15 m average soil water content.

2.4.4.Overall comparison

The overall performance of each model is evaluated through the statistical indexes described in Materials and Methods section, Eqs. 2.12, 2.13, 2.14 and 2.15. Table 2.6 shows the indexes of the calibration and validation procedures for both sites. The indexes are a weighted average over depths along the profile. The three models are calibrated by comparison measured and simulated soil water content at Cerese site for the year 2002 and at Caviaga site for the year 2003. The models validation was performed on the 2003 data set at Cerese site and on the 2002 data set at Caviaga site. For the calibration of Caviaga site we use the data collected during the 2003 because of the reduced number of 2002 data measured (291, see Materials and Methods section). Cerese and Caviaga measurements do not show any evidence of non-equilibrium flow; therefore, in the MACRO model the effect of macroporosity is reduced to zero consistently with field measurements where cracking was not observed.

Table 2.6. Main performance indexes for the three models in both sites Cerese and Caviaga.

Indexes		Year	Cerese			Caviaga		
			SWAP	CropSyst	MACRO	SWAP	CropSyst	MACRO
CRM	Min -inf Max +inf Optimum 0	2002	-0.036	-0.032	-0.019	-0.052	-0.005	-0.102
		2003	-0.049	-0.028	-0.038	0.010	-0.040	0.080
RMSE ($cm^3 cm^{-3}$)	Min 0 Max +inf Optimum 0	2002	0.032	0.030	0.035	0.037	0.037	0.045
		2003	0.026	0.021	0.024	0.027	0.034	0.037
R	Min -1 Max +1 Optimum +1	2002	0.742	0.791	0.640	0.503	0.389	0.484
		2003	0.751	0.708	0.764	0.713	0.783	0.731
EF	Min -inf Max +1 Optimum +1	2002	0.310	0.266	0.100	-0.049	0.066	-0.447
		2003	0.415	0.297	0.418	0.234	0.026	-0.256

For the three models application at Cerese CRM is negative both in the validation and in the calibration years. RMSE values lie between 0.021-0.035 with a clear improving between years. The correlation index values are not very different between years and models, while the EF increases from calibration to validation years. For Caviaga site, with few exceptions, all the indexes are better for the calibration year (2003) than those of the validation year (2002). CRM was close to zero in all considered combinations of years a model. RMSE values range from 0.027 to 0.037 and from 0.037 to 0.045 in the calibration and validation year, respectively. The r values are remarkably lower in the validation years (average 0.46), respect to the calibration one (average 0.74). EF showed a behaviour similar to r, and in the case of MACRO, EF reach values strongly below zero. RMSE values agree with those showed in previous studies. Sheikh and van Loon (2007) reported several RMSE values obtained in calibration-validation procedures. They reported values from Heathman et al. (2003), Crescimanno and Garofalo (2005), Mertens et al. (2005), Singh (2005), Wegehenkel (2005), and Sheikh and van Loon (2007). Most of these results have a range of 0.03-0.05; few horizons showing lower (0.01-0.02) and higher (0.08-0.10) values. Eitzinger et al. (2004), comparing SWAP, CERES and WOFOST models, obtained RMSE values ranging from 0.007 to 0.070 for different soils, models and crops. The worsening of the difference-based indexes between the calibration and validation year can be mainly attributed to the models different performance in the upper and lower part of soil profile. As example of this, Figure 2.5 shows that: (i) the uppers layers contribute to the profile-averaged RMSE to a large extent respect the lower layers; (ii) the differences between 2003 and 2002 decrease as depth increasing. Particularly, higher values result for the 0-0.15, 0.2 and 0.3 m depth. The reduction of elementary water flow mechanisms complexity through soil profile (i.e. infiltration, redistribution, uptake, evapotranspiration vs. drainage and capillary rise) can explain higher differences in the upper horizons than in the lower ones. On the other side, absolute errors at 0-0.15 m depth can be also affected by the higher inaccuracy of TDR surface measurements respect to those measured at lower depths (Robinson et al., 2003).

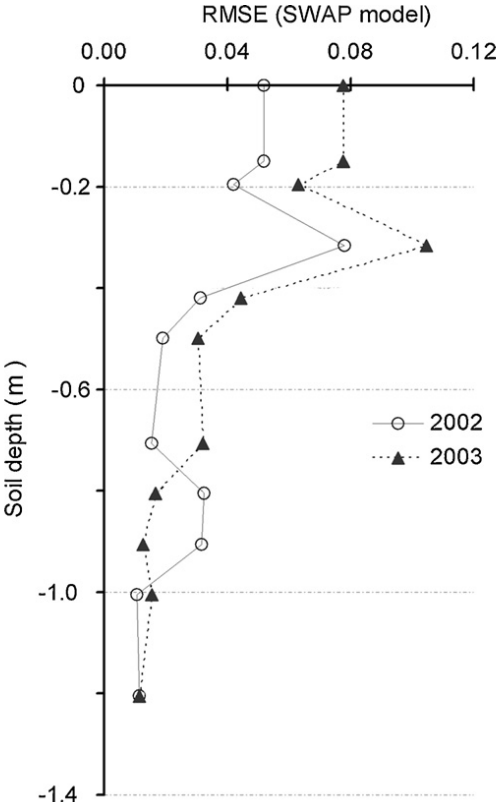


Figure 2.5. RMSE profile (2002 and 2003) for SWAP model application.

2.5. Conclusions

A comparison of the Richards-based codes SWAP, CropSyst and MACRO was performed for a 2-years of maize-cultivation on an Alfisol and a vertic Inceptisol located in the Po valley, in Northern Italy using (i) difference-based indexes (CRM and RMSE), (ii) correlation statistics (r and EF), (iii) plot of measured and estimated water content vs. time, and (iv) plot of measured and estimated water content profiles.

The comparison showed good performance of the all three models.

As far as CRM index is concerned, the three models generally overestimated the prediction, excepts MACRO in Caviaga. In particular, decreasing performance of SWAP and MACRO in Cerese and Caviaga validation year was remarkable, while, on the contrary, CropSyst showed little differences in performances between calibration and validation years.

None of the models consistently outperformed the others in terms of RMSE. All the three models gave good results with slight differences between the two soils and between years.

Analyzing the other two indexes (r and EF), generally, SWAP and CropSyst followed the water content variation slightly better than MACRO.

Summarizing, models validation performance is consistent with calibration results. This is relevant because of the remarkable differences of the occurring climate, being 2002 a wet year and 2003 a very dry year. Furthermore, once properly calibrated, SWAP (in both sites) and CropSyst (in Cerese site)showed an overall better performance, in spite of the similar hydraulic parameterization of SWAP and MACRO.

Analyzing the performance on single horizons and on one-directional drying process in bare soils, some differences between the models were noticed. The most important difference consisted in performances of the shallow water dynamics simulations. It was demonstrated, among others by van Dam and Feddes (2000), the need of as small as possible compartments both for infiltration and evaporation simulations. In fact, because in CropSyst it is impossible to adopt such small compartment, CropSyst underperformed respect to SWAP and MACRO. At the bottom of soil profiles, all the three models gave good agreement between measured and simulated water content in presence and absence of water table.

Another important point concerns the parameters calibration forcing to best fitting measured and estimated data. In such respect, SWAP and MACRO very rapidly fit the measured $\theta(t,z)$ just adapting only slighting measured θ_0 and K_0 parameters. This feature is mainly due to feasibility of the van Genuchten-Mualem parameterization in describing hydraulic properties while CropSyst does not allow values of h_b and λ outside of a relatively narrow interval

($0.5<|h_b|<8$; $1.5< \lambda <8$); our measured data in some cases lies outside of this range. Due to the impossibility to use, (even if in few cases) the measured parameters the model loose a part of its 'physical basis' towards an increasing of its empiricism.

Summarizing, relatively to the test we performed and taking into account that all the three models gave very satisfactory results we can however rank the tested models in the following order SWAP, CropSyst and MACRO.

2.6. Acknowledgements

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Chapter 3

Nitrate leaching under maize cropping systems in Po valley (Italy)

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Keywords

intensive cropping system, nitrogen fertilization, nitrate leaching, suction cup, irrigation.

3.1. Abstract

In order to assess the nitrate (NO_3-N) leaching from continuous maize (Zea mays L.) cropping system in Po Plain (Northern Italy), a monitoring of nitrogen dynamics was carried out in 6 fields, under the ordinary management of the farmer, for a period from 2 to 5 years. Fertilization ranged from 209 to 801 kg NO_3-N ha^{-1}year^{-1}, using both organic and mineral fertilizer. Maize biomass ranged from 15 to 32 t ha^{-1}, nitrogen uptake from 150 to 400 kg ha^{-1}. At 5 depth soil water solution were sampled every 7-30 days using suction cups; soil water content was measured daily by TDR equipment. Soil water [NO3-N] varied from 0 up to 110 mg L^{-1}, with highest concentration after fertilizer application. Once validated against observed soil water content, SWAP model was applied to calculate the drainage flux. Annual leaching was calculated by multiplying drainage flux by soil water [NO_3-N]. Leaching ranged from 14 to 321 kg ha^{-1} year^{-1}, according to rainfall, fertilization and irrigation management, crop N removal, being mainly affected by N surplus. Proper irrigation, sidedress fertilization and catch crop allow for a substantial reduction of the leaching, being the agricultural management more affecting nitrogen losses than soil type.

3.2. Introduction

Since the European Union Directive 91/676 (Nitrates Directive) compels Member States to be compliant with mandatory standards, such as the maximum permissible nitrate concentration in groundwater of 50 mg L^{-1}, then it is definitely important to monitor soil solution at field scale in order to assess the risk of nitrate pollution from agriculture. A reliable in situ measurement of the soil solution NO_3-N concentration is important to evaluate the actual nitrate leaching through unsaturated soil. A proper monitoring site, at field scale, helps in the assessment of the impact of different agronomic management, such as fertilization and irrigation, on groundwater quality. In fact, nitrogen amount exceeding plant demand may be lost as nitrate by water drainage, reaching the groundwater.

Frequently (Prunty and Montgomery, 1991; Thomsen, 2005; Peu et al., 2007) lysimeter is employed in the assessment of groundwater nitrate pollution, although can never fully reflect a full-scale field management (Trankler et al., 2005). Moreover other several sources of errors can occur, mainly side wall flow (Corwin, 2000) and differences in drainage between lysimeter and field condition, due to the different bottom boundary conditions.

A large amount of literature reported data collected from field trials specifically set for the leaching monitoring itself, where the chief experimental factors were soil type (Hack-Ten Broeke, 2001), type of organic manure (Mantovi et al., 2006; Mirschel et al., 2007), cropping system (Booltink, 1995; Mirschel et al., 2007), irrigation (Zatorelli et al., 2009) or a combination of such factors (Johnson et al., 1997; Askegaard et al., 2005, Sibley et al., 2009). Since nitrate leaching occurs in most of the intensively cropped areas, then it is more representative to measure leaching related variables in fields managed according farmers' ordinary practices. Hack-Ten Broeke (2001) calculated nitrate leaching by measurements of soil moisture condition and nitrate concentration which was sampled from porous cups at 1 m depth once a month over 4 years at 6 monitoring sites in experimental farm 'De Mark' in Netherlands under sandy soil condition, where silage maize, grassland and Italian ryegrass were cropped under controlled management. The calculated annual mean nitrate concentration at 1 m depth was 67 mg L^{-1}; the agronomic management resulted crucial in affecting nitrate losses. Beaudoin et al. (2005) quantified nitrogen leaching over 8 years below the rooting zone in different soil types, crop rotations and actual farming practices at 36 monitoring sites on the basis of soil mineral nitrogen, measured on soil cores taken up to 120 cm depth 3 times per year, and modelled water percolation. Nitrate concentration was mainly affected by water holding capacity of soil, ranging from 31 mg L^{-1} in deep loamy soils to 92 mg L^{-1} in shallow sandy soils. Mean calculated amount of leached nitrogen below the rooting depth was 8 to 45 kg NO_3-N ha^{-1} $year^{-1}$. Employing porous cups as device for monitoring nitrate leaching, different authors evaluated the potential risk of nitrate pollution under field conditions (Lord and Shepherd, 1993; Poss et al., 1995; Askegaard et al., 2005; Zatorelli et al., 2007). According to their studies, nitrate leaching may be estimated by multiplying nitrate concentration in soil solution by drainage flux. Such data are easily measurable at field scale employing suction cups, giving a reliable measurement of the concentration of nitrate in the soil solution, and a device, such as time domain reflectometry technique (TDR), providing data of the soil water content. Hydrological dynamics simulation models or simple algorithms can be used to calculate drainage flux when based on observed soil water content measurements (Jackson, 2003; Askegaard et al., 2005; Gaur et al. 2006; Verbist et al., 2009).

Field monitoring is even more important in the case of intensive crop-livestock farming systems where large amount of nitrate may be drained to groundwater altering its quality, due to high amount of nitrogen fertilizers: Po Valley is characterized by this kind of farming systems. Such area accounts for 7 ml of livestock units, and a density of about 1.7 LSU (equal to 500 kg) ha^{-1} of utilized agricultural area (UAA). Furthermore it has the largest aquifer in Europe and 67% of the UAA is defined as Nitrate Vulnerable Zone (ISTAT, 2010a). The prevalent crops grown are grain and silage maize (Zea mays L.) being key crops of intensive agricultural systems in such area (Grignani et al., 2007). Continuous maize cropping system has an high potential risk of nitrate leaching particularly when there is a large supply of nitrogen and water (Acutis et al., 2000).

The objective of this study was to evaluate the nitrogen dynamics in 6 fields in Po Valley, in grain and silage maize fields under the ordinary management of the farmer, over a period from 2 to 5 years. The collected data sets are also suitable to be used in modelling application, being representative of the studied area.

3.3. Materials and methods

3.3.1. Site description

Figure 3.1. Location of the five monitoring sites: Italy (A), Lombardy Region (B).

Experimental data sets were collected over a maximum of 5 years in 5 sites, mostly sown to maize: Caviaga (LO, province of Lodi, 45.31°N, 9.50°E, 72 m a.s.l.), Cerese (MN1 and MN2, province of Mantova, 45.12°N, 10.79°E, 20 m a.s.l.), Landriano (PV, province of Pavia, 45.28°N, 9.27°E, 84 m a.s.l.), Ghisalba (BG, province of Bergamo, 45.69°N, 9.75°E, 178 m a.s.l.), Luignano (CR, province of Cremona, 45.17°N, 9.9°E, 57 m a.s.l.), located in Lombardy plain (Po Valley). Monitoring took place in two adjacent fields at MN site: at MN1 from 2002 to 2004, at MN2 from 2005 to 2006. Results of nitrate measurements are presented for these sites (one on each of five farms) which are representative of the farmers' common practices. Figure 3.1 shows the location of the monitoring sites.

3.3.2. Soil characteristics and climate

A soil description of each site is briefly given according to the Soil Taxonomy of USDA Soil Conservation Service (USDA, 1977). LO site has a fine loamy over sandy, mixed, superactive, mesic, deep, moderately acid Ultic Hapludalf, widely unsaturated in the exchange complex. MN1 site has a fine, mixed, superactive, mesic, Vertic Calciustepts soil. It is a clay loam soil, characterized by a deep calcic horizon and high content of calcium carbonate with an exchange complex always saturated (Bonfante et al., 2010). MN2 has fine, mixed, active, mesic, Typic Calciustept soil. BG site has a fine loamy, mixed, superactive, mesic, Typic Hapludalf soil. BG soil profile is characterized by a remarkable stone content whose value ranges from 34 kg kg^{-1} in the upper soil to 55 kg kg^{-1} at 1.3 m depth. PV site has a coarse silty, mixed, superactive, mesic, Oxyaquic Haplustept soil. CR site has a fine silty, mixed, superactive, mesic, Inceptic Haplustalf soil. Soil physical and chemical properties (texture, structure, organic matter, pH, soil cation exchange capacity) of each site are reported in Table 3.1. Soil hydraulic properties were also measured on undisturbed soil samples of each horizon according Reynolds and Elrick (2002). Mean annual rainfall over 22 years (1988–2009) was 704, 690, 1070, 925, 721 mm year-1 at LO, MN (1 and 2), BG, PV and CR, respectively. Over these 22 years mean maximum and minimum temperature (°C) for the maize cropping season, from April to September, in the same period were: 26.9 and 15.3 at LO; 27.9 and 16.1 at MN(1 and 2); 26.4 and 14.7 at BG; 28.6 and 14.7 at PV; 27.1 and 14.2 at CR.

Table 3.1. Main physical and chemical characteristics of the soil in the experimental fields.

Soil horizon		Bottom depth	Sand 2-0.05 mm	Silt 0.05-0.002 mm	Clay, <0.002mm	Bulk density	pH (H_2O)	Organic carbon	$CaCO_3$	Cation exchange capacity
		[m]	[%]	[%]	[%]	[Mg m^{-3}]	[-]	[%]	[%]	[cmol(+) kg^{-1}]
LO	**Ap1**	**0.2**	**49.5**	**32.6**	**17.9**	**1.5**	**5.9**	**0.8**	**0.0**	**15.4**
	Ap2	**0.4**	**49.1**	**33.2**	**17.7**	**1.5**	**6.0**	**0.8**	**0.0**	**12.5**
	Bt1	**0.5**	**46.8**	**31.4**	**21.8**	**1.7**	**6.2**	**0.4**	**0.0**	**12.5**
	Bt2	**0.8**	**74.5**	**12.1**	**13.4**	**1.5**	**6.7**	**0.2**	**0.0**	**9.9**
	BC	**1.1**	**83.7**	**6.3**	**10.0**	**1.5**	**6.8**	**0.1**	**0.0**	**8.9**
	C	**1.4**	**86.6**	**7.4**	**6.0**	**1.5**	**7.0**	**0.1**	**0.0**	**7.7**
MN1	**Ap**	**0.3**	**21.4**	**44.0**	**34.6**	**1.4**	**8.1**	**1.1**	**7.0**	**22.9**
	Bss1	**0.5**	**16.3**	**42.0**	**41.7**	**1.4**	**8.2**	**0.7**	**6.0**	**20.5**
	Bss2	**0.7**	**13.6**	**39.4**	**47.0**	**1.4**	**8.3**	**0.5**	**1.0**	**26.1**
	Bk	**0.9**	**22.9**	**50.3**	**26.8**	**1.5**	**8.5**	**0.4**	**45.0**	**15.1**
	C	**1.1**	**88.2**	**7.0**	**4.8**	**1.5**	**8.7**	**0.2**	**40.0**	**-**
MN2	**Ap**	**0.4**	**30.6**	**42.0**	**27.3**	**1.4**	**8.2**	**1.7**	**11.0**	**27.2**
	Bw	**0.6**	**7.5**	**56.5**	**36.1**	**1.4**	**8.4**	**0.9**	**14.0**	**26.0**
	BC	**0.8**	**2.5**	**66.4**	**31.0**	**1.4**	**8.6**	**0.5**	**50.0**	**19.1**
	Ck	**1.0**	**9.7**	**70.7**	**19.6**	**1.4**	**8.7**	**0.4**	**73.0**	**16.5**
	C	**1.3**	**21.9**	**68.4**	**9.7**	**1.4**	**8.7**	**0.1**	**58.0**	**10.8**
BG	**Ap1**	**0.4**	**27.3**	**56.7**	**16.0**	**1.3**	**7.5**	**1.9**	**2.0**	**15.0**
	Bt1	**0.5**	**39.2**	**45.8**	**15.0**	**1.5**	**7.7**	**0.8**	**2.0**	**15.2**
	Bt2	**0.8**	**33.5**	**44.3**	**22.3**	**1.5**	**8.0**	**0.5**	**0.0**	**15.9**
	BC	**1.0**	**31.2**	**43.6**	**25.3**	**1.4**	**8.2**	**0.5**	**0.0**	**18.8**
	2C1	**1.2**	**85.9**	**11.1**	**3.0**	**1.4**	**8.5**	**0.2**	**28.0**	**7.1**
PV	**Ap1**	**0.4**	**27.3**	**56.7**	**16.0**	**1.7**	**7.5**	**1.9**	**2.0**	**15.0**
	Bt1	**0.5**	**39.2**	**45.8**	**15.0**	**1.6**	**7.7**	**0.8**	**2.0**	**15.2**
	Bt2	**0.8**	**33.5**	**44.3**	**22.3**	**1.5**	**8.0**	**0.5**	**0.0**	**15.9**
	BC	**1.0**	**31.2**	**43.6**	**25.3**	**1.5**	**8.2**	**0.5**	**0.0**	**18.8**
	2C1	**1.2**	**85.9**	**11.1**	**3.0**	**1.5**	**8.5**	**0.2**	**28.0**	**7.1**
CR	**Ap**	**0.4**	**35.5**	**49.8**	**14.7**	**1.5**	**6.6**	**1.5**	**0.0**	**24.7**
	Bt	**0.7**	**41.5**	**29.4**	**29.1**	**1.5**	**7.2**	**0.5**	**1.0**	**17.9**
	BC	**1.0**	**69.0**	**13.9**	**17.1**	**1.5**	**7.2**	**0.6**	**0.0**	**12.8**
	C	**1.5**	**31.7**	**50.0**	**18.3**	**1.5**	**7.4**	**0.4**	**0.0**	**12.8**

3.3.3. Agricultural practices

The cropping systems included silage and grain maize, winter wheat (Triticum aestivum L., ww), double annual crop rotation of Italian ryegrass (Lolium multiflorum Lam.) as catch crop in autumn and winter and silage maize in spring and summer. Crop-related variables, as phenological stages, scaled to a decimal scale called BBCH (2001), leaf area index (m^2 m^{-2}), nitrogen uptake (kg ha^{-1}), above ground biomass (kg ha^{-1}), harvest index (%) were collected over the whole period. Annual data of dry matter production and nitrogen uptake are shown in Table 3.2 where sowing and harvest dates are also reported.

Table 3.2. Data of crop-related variables observed over the monitoring period: above ground biomass (AGB, kg ha^{-1}) and plant nitrogen uptake (N Uptake, kg ha^{-1}). Standard error: ±.

Site	Year	AGB	N Uptake	Crop	Sowing date	Harvest date
LO	2002	22964±650	219±29	silage maize 700	March 20, 2002	August 19, 2002
	2003	15508±367	147±28	silage maize 700	March 19, 2003	August 5, 2003
	2004	18747±103	212±16	silage maize 700	April 27, 2004	August 19, 2004
	2005	18415±520	201±17	silage maize 700	April 6, 2005	August 17, 2005
	2006	15833±329	190±5	winter wheat	October 1, 2005	June 27, 2006
MN1	2002	32495±863	425±37	grain maize 700	March 12, 2002	September 20, 2002
	2003	28037±521	290±12	silage maize 700	March 13, 2003	August 7, 2003
	2004	20482±543	198±9	grain maize 600	March 30, 2004	August 18, 2004
MN2	2005	26550±589	289±7	grain maize 700	March 19, 2005	September 23, 2005
	2006	28123±310	289±13	grain maize 700	March 28, 2006	September 5, 2006
BG	2005	22522±62	197±9	grain maize 600	March 31, 2005	October 19, 2005
	2006	22934±51	236±6	silage maize 700	April 18, 2006	September 20, 2006
	2007	23945±58	249±9	grain maize 600	April 11, 2007	September 15, 2007
	2008	23815±632	234±21	grain maize 600	March 31, 2008	September 26, 2008
	2009	26454±538	280±12	silage maize 700	April 2, 2009	September 25, 2009
PV	2006	22764±604	235±23	grain maize 700	April 14, 2006	September 11, 2006
	2007	26023±737	208±8	grain maize 600	April 24, 2007	September 19, 2007
	2008	4997±498	69±6	It. Ryegrass	October 2, 2007	May 10, 2008
	2008	20993±557	163±9	silage maize 500	May 6, 2008	September 25, 2008
	2009	6703±774	94±7	It. Ryegrass	October 19, 2008	May 10, 2009
	2009	21930±582	222±14	silage maize 500	May 21, 2009	September 23, 2009
CR	2005	27861±72	293±18	grain maize 700	March 24, 2005	September 27, 2005
	2006	16779±326	151±20	silage maize 700	April 4, 2006	August 22, 2006

Fertilization features differed from site to site according to the common practices of the studied area. Amount, type and period of fertilization were recorded over the monitoring period. Nitrogen fertilization has been applied by farmers as shown in Table 3.3.

Organic fertilization had an mean annual amount of 235, 498, 245, 222, 228, 0 kg N ha^{-1}year^{-1}, and nitrogen mean annual amount as mineral fertilizers were 118, 192, 161, 259, 146, 309 kg N ha^{-1}year^{-1} at LO, MN1, MN2, BG, PV, CR, respectively. At MN sites organic manure has been applied in autumn on bare soil according to the common practice of this area of the Po Plain where the soil does not drain easily. Moreover, when maximum volumetric capacity of slurry tank is reached farmers are forced to apply organic manure in autumn. Maize crop has an high water demand under Po Plain climatic condition. The irrigation period starts about in June and ends in early August. The number of irrigation events depends on the irrigation method, soil and the cropping system. In the case of sprinkler irrigation events are typically 4-7 per year and the mean amount for each irrigation is about 45 mm, whereas border irrigation has small efficiency that is why mean water mean amount is 80 mm. In the latter case, typical number of irrigation ranges from 3 to 6. Mean water amount which farmers applied per cropping season (from June to August) was 350 mm at BG, 300 mm at LO and CR, 280 mm at MN1 and MN2, 240 mm at PV. The monitoring period rainfall did not deviate substantially from the mean values measured from 1990 to 2009.

Table 3.3. Nitrogen fertilization amount (kg N ha^{-1} year^{-1}) over the whole monitoring period in each sites. SS= sewage sludge (7.7 g N kg^{-1}) DS= dairy slurry (DS1 4.3, DS2 3.5, DS3 2.2 g N kg^{-1}), PS= pig slurry (3.1 g Nkg^{-1}), DM= dairy manure (2.5 g N kg^{-1}), St=molasses stillage (30 g N kg^{-1}), Ur=urea (46 % of N), AM= ammonium nitrate (26% of N), NP and NPK= compound fertilizers (18 and 10 % of N , respectively). Org., Min., Tot.=mean annual amount of organic, mineral and total nitrogen fertilization.

Site	Year	Org.	Min.	Tot.	Single application									
LO	2002	196	126	322	01/03/02	196 (SS)	20/03/02	33 (NP)	15/05/02	93 (AN)				
	2003	210	126	336	14/02/03	210 (SS)	19/03/03	33 (NP)	15/05/03	93 (AN)				
	2004	256	126	382	19/03/04	256 (SS)	27/04/04	33 (NP)	15/05/04	90 (AN)				
	2005	305	86	391	22/03/05	305 (SS)	05/04/05	11 (NP)	15/05/05	75 (AN)				
	2006	210	125	335	01/04/06	47 (AN)	01/09/06	210 (SS)						
MN1	2002	350	196	546	02/10/01	357 (DS1)	29/04/02	46 (AN)	20/05/02	150 (Ur)	19/10/02	357 (DS1)		
	2003	386	192	578	24/04/03	40 (AN)	23/05/03	152 (Ur)	18/08/03	209 (PS)	28/08/03	177 (DS1)		
	2004	609	192	801	21/04/04	46 (AN)	27/04/04	166 (Ur)	20/08/04	178 (PS)	25/08/04	310 (DM)	27/08/04	121 (DS1)
MN2	2005	210	212	422	05/11/04	245 (DS2)	09/05/05	138 (Ur)						
	2006	280	110	390	10/11/05	245 (DS2)	23/05/06	110 (Ur)						
BG	2005	210	255	465	03/08/05	210 (DS2)	22/03/05	53 (NPK)	24/05/05	152 (Ur)	10/06/05	50 (Ur)		
	2006	242	204	446	28/03/06	242 (DS2)	13/04/06	52 (NPK)	17/04/06	102 (Ur)	07/06/06	50 (Ur)		
	2007	208	255	463	08/03/07	208 (DS2)	25/03/07	53 (NPK)	29/05/07	155 (Ur)	06/06/07	47 (Ur)		
	2008	238	291	529	13/03/08	238 (DS2)	18/03/08	52 (NPK)	21/03/08	101 (Ur)	14/05/08	138 (Ur)		
	2009	210	291	501	10/03/09	201 (DS2)	22/03/09	45 (Ur)	10/04/09	101 (Ur)	24/04/09	67 (Ur)		
PV	2006	92	117	209	24/03/06	92 (St)	22/05/06	117 (Ur)						
	2007	200	96	296	18/04/07	200 (DS3)	06/06/07	96 (Ur)						
	2008	368	96.6	465	27/03/08	170 (Ur)	03/06/08	97 (Ur)	06/10/08	124 (DS3)				
	2009	258	104	362	13/03/09	35 (Ur)	18/05/09	240 (DS)	26/06/09	69 (Ur)				
CR	2005	-	304	304	24/03/05	194 (Ur)	03/05/05	110 (Ur)						
	2006	-	314	314	04/04/06	157 (Ur)	15/05/06	158 (Ur)						

3.3.4. Monitoring soil solution concentration and water content

Nitrogen concentration in soil solution was sampled by ceramic cups used to extract soil solution under pressure. The ceramic cups were usually sampled almost weekly although samples could not be collected when the soil was too dry, especially in the case of the shallow cups installed at 0.3 m of depth. At each site suction cups were placed at 5 depth (Table 3.4) with 3 replicates at LO and MN1 and 2 replicates at the other sites. Suction cups had an outside diameter 3.0 cm and were glued to the lower ends of PVC pipes. The length of the PVC pipe was installed approximately 20 cm above ground level when the cup was located at its reference depth as suggested by Poss et al. (1995). In order to ensure proper hydraulic contact between ceramic cup and soil, samplers were installed in a hole of similar diameter pouring the gap with the soil removed from the hole and mixed with diatomite flour. Samples were obtained by applying suction of up to 70 kPa using a portable pump. Samples were then refrigerated at 4°C and analyzed using a colorimetric methods of Hendriksen and Selmer-Olsen (1970). Ammonium concentrations were also analyzed but values were always negligible (< 0.5 mg L^{-1}) and are not discussed further.

Soil water content (SWC) was measured by time domain reflectometry technique (TDR), applying the empirical Topp's formula to the measured soil bulk dielectric permittivity (Robinson et al., 2003).

Table 3.4. Suction cups and TDR (time domain reflectometry) probes installation depths.

LO	MN1	MN2	BG	PV	CR
0.3	0.3	0.3	0.4	0.3	0.3
0.5	0.5	0.5	0.7	0.5	0.5
0.8	0.7	0.7	0.9	0.8	0.8
1.2	1	1	1.2	1	1
1.4	1.3	1.3	1.3	1.3	1.3

Probes, in 2 or 3 replicates, were placed at different depth (from 0.05 to 1.3 m below soil surface) close to ceramic cups and connected by a 36-channels multiplexer to a cable tester Tektronix 1502/C. SWC was measured every 4 h. Bonfante et al (2010) reported details of SWC measurements obtained in two of the 5 monitoring sites (LO and MN).

3.3.5. Nitrate leaching calculation

Nitrate leaching was estimated using the trapezoidal rule suggested by Lord and Shepherd (1993), which assumes that nitrate concentrations in the extracted soil water solution represented mean flux concentration. The total nitrogen leached (*N leached*) in each sampling interval, in kg ha^{-1}, was:

$$Nleached = \frac{0.5(c1 + c2)v}{100} \qquad [3.1]$$

where *c1* and *c2* are successive pairs of sampling occasions (mg $N0_3$-NL^{-1}), and the drainage volume between sampling occasions (*v*, mm). Drainage values at each site were simulated using SWAP simulation model (Van Dam et al., 1997; Van Dam and Feddes, 2000). SWAP model was chosen because it showed better performance respect to other hydrological models in similar environments (Bonfante et al., 2010).

3.4. Results

3.4.1. NO_3-N concentrations in suction cups

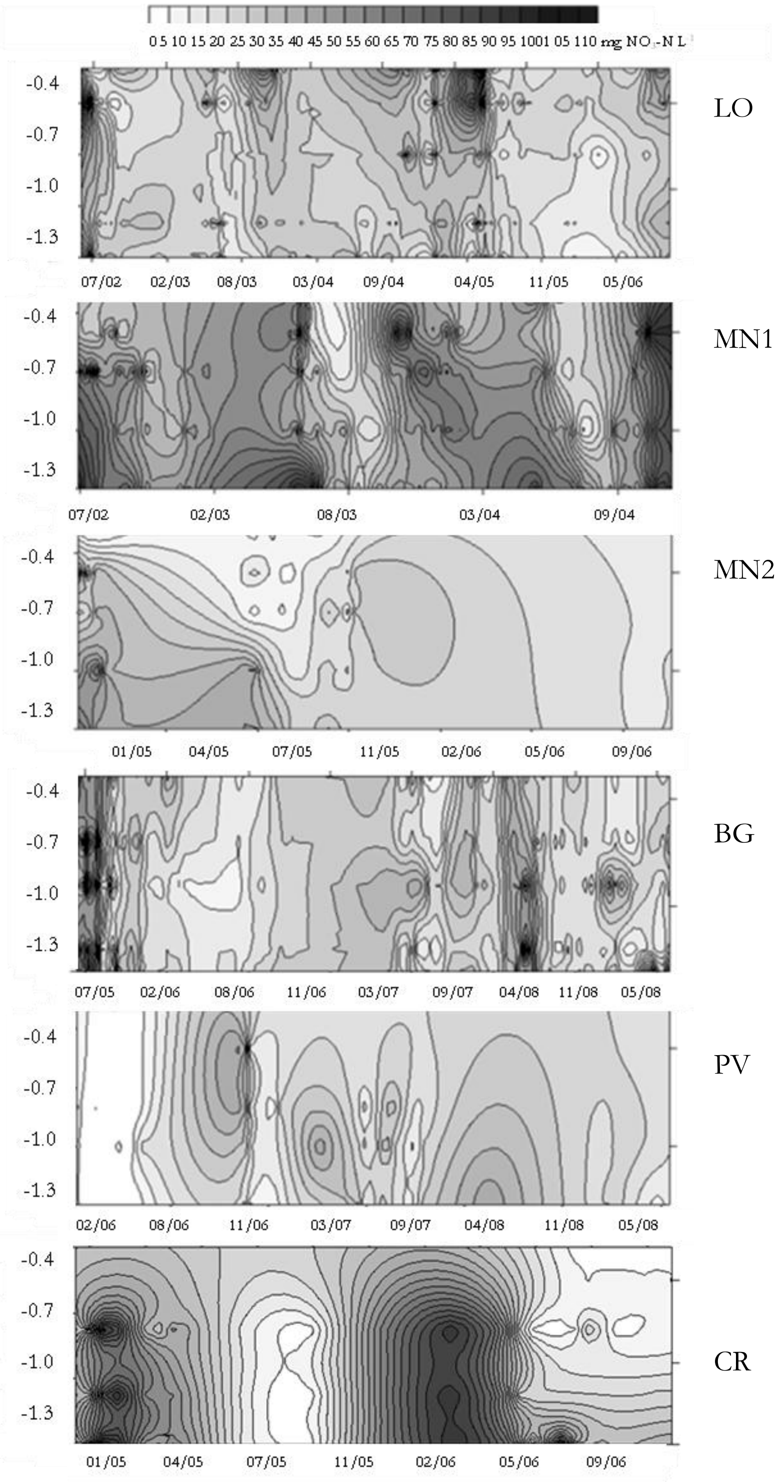
Table 3.5. Observed values of NO_3-N concentration (mg L^{-1}) of the suction cups water.

	depth (m)	mean	min	max
LO	0.3	29±0.76	2	109
	0.5	29±0.92	4	98
	0.8	23±1.16	4	61
	1.2	24±0.66	4	67
	1.4	21±0.82	2	71
MN1	0.3	40±1.41	9	76
	0.5	56±2.66	7	101
	0.7	48±1.42	11	83
	1	48±1.57	8	86
	1.3	59±1.02	15	108
MN2	0.3	4±0.33	0	12
	0.5	17±0.33	1	37
	0.7	14±1.29	5	36
	1	26±2.4	14	80
	1.3	30±3.7	2	65
BG	0.4	24±0.75	6	72
	0.7	25±1.13	6	83
	0.9	27±1.24	0	86
	1.2	24±0.61	1	84
	1.3	9±0.31	1	45
PV	0.3	4±0.9	0	12
	0.5	12±0.68	0	46
	0.8	14±0.84	0	41
	1	16±1.31	0	45
	1.3	13±0.67	0	52
CR	0.3	2±0.03	0	29
	0.5	11±0.31	0	12
	0.8	33±0.91	2	105
	1	46±1.09	4	108
	1.3	13±1.01	3	52

Mean, minimum and maximum values of NO_3-N soil water solution (mg L^{-1}) at different depths are reported in Table 3.5. Large differences in NO_3-N concentrations were recorded at the monitoring sites.In Figure 3.2 a contour plot of soil water solution NO_3-N concentration over the monitoring time through soil profile is shown at each monitoring site. High values were measured in correspondence of high N fertilizer supply. The variability in NO_3-N concentrations were remarkable at LO due to the soil profile characterized by a low water holding capacity, together with considerable N applied. At this site high concentrations were recorded in summer 2002, winter 2003, spring and summer 2005.

High values were observed at MN1, where the mean value of NO_3-N over the monitoring period was 58 mg L^{-1} at the deepest depth, in correspondence to fertilization and irrigation period. Moreover, in autumn 2003, after maize harvest, high concentrations were recorded, as well as in autumn 2004 due to large N fertilization amount (mean annual of 642 kg N ha^{-1} $year^{-1}$). On average at BG low concentrations were recorded in summer, with exception of 2005 and 2008 due to lower water supply. At PV NO_3-N values were overall low; only after manure N application in autumn 2006 and 2007, mean NO_3-N concentration of 30 mg L^{-1} was scored. Values close to 100 mg L^{-1} of NO_3-N were observed close to inorganic N application at CR. NO_3-N concentration of 83 mg L^{-1} was observed at the end of maize growing season. This value is higher than the average of the other sites, although here only mineral nitrogen is used as a fertilizer. Moreover, both in 2005 and 2006 in spring and summer a remarkable percolation of NO_3-N from upper to bottom layer occurred.

Figure 3.2. NO_3-N concentrations (mg L^{-1}) in soil water solution extracted by ceramic cups through soil profile. Bottom depths were: 1.4 m at LO, 1.3 m at MN, MN2, BG, and PV and 1.5 at CR. Monitoring period were: 2002- 2006 at LO, 2002-2004 at MN1, 2005-2006 at MN2, 2006-2009 at BG, 2006-2009 at PV, 2005-2006 at CR..


0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 1001 05 110 mg NO3-N L
LO
-0.4
-0.7
-1.0
-1.3
07/02 02/03 08/03 03/04 09/04 04/05 11/05 05/06
MN1
-0.4
-0.7
-1.0
-1.3
07/02 02/03 08/03 03/04 09/04
MN2
-0.4
-0.7
-1.0
-1.3
01/05 04/05 07/05 11/05 02/06 05/06 09/06
BG
-0.4
-0.7
-1.0
-1.3
07/05 02/06 08/06 11/06 03/07 09/07 04/08 11/08 05/08
PV
-0.4
-0.7
-1.0
-1.3
02/06 08/06 11/06 03/07 09/07 04/08 11/08 05/08
CR
-0.4
-0.7
-1.0
-1.3
01/05 04/05 07/05 11/05 02/06 05/06 09/06

3.4.2. Soil water content and drainage

Simulated values of SWC were consistent with SWC observed data. SWAP model was previously calibrated at each site slightly modifying the hydrological parameters measured in laboratory on undisturbed soil cores (Bonfante et al., 2010). Validation was carried out by using large monitoring sites data set consisting in 3500 SWC data of soil profile from 0.8 to 1.3 m depth. The scored values of overall fitting of 3500 data showed SWAP reliability in simulating SWC (statistics indexes: relative root mean square error, RRMSE=4.6%, modelling efficiency, EF=0.95). Figure 3.3 shows regression line between observed and simulated data. Moreover, Bonfante et al. (2010) reported results of good performance of SWAP model in simulating SWC at all investigated depths of LO and MN soil profile (r= 0.75 and EF=0.41).

Mean drainage amount, simulated by SWAP model, was 539, 393, 458, 576, 112 and 198 mm at LO, MN1, MN2, BG, PV and CR, respectively.

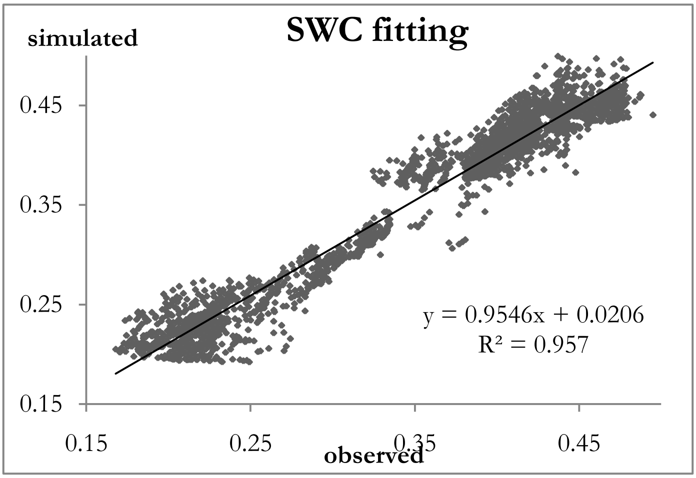


Figure 3.3. Observed and simulated soil water content (SWC, m^3 m^{-3}) by SWAP at every monitoring depth at every site.

3.4.3. Nitrate leaching calculation

Mean monthly nitrogen leaching (kg NO_3-N ha^{-1} $year^{-1}$) and water input (rainfall and irrigation supply) are shown in Figure 3.4. Differences in losses' trend are detectable from site to site.

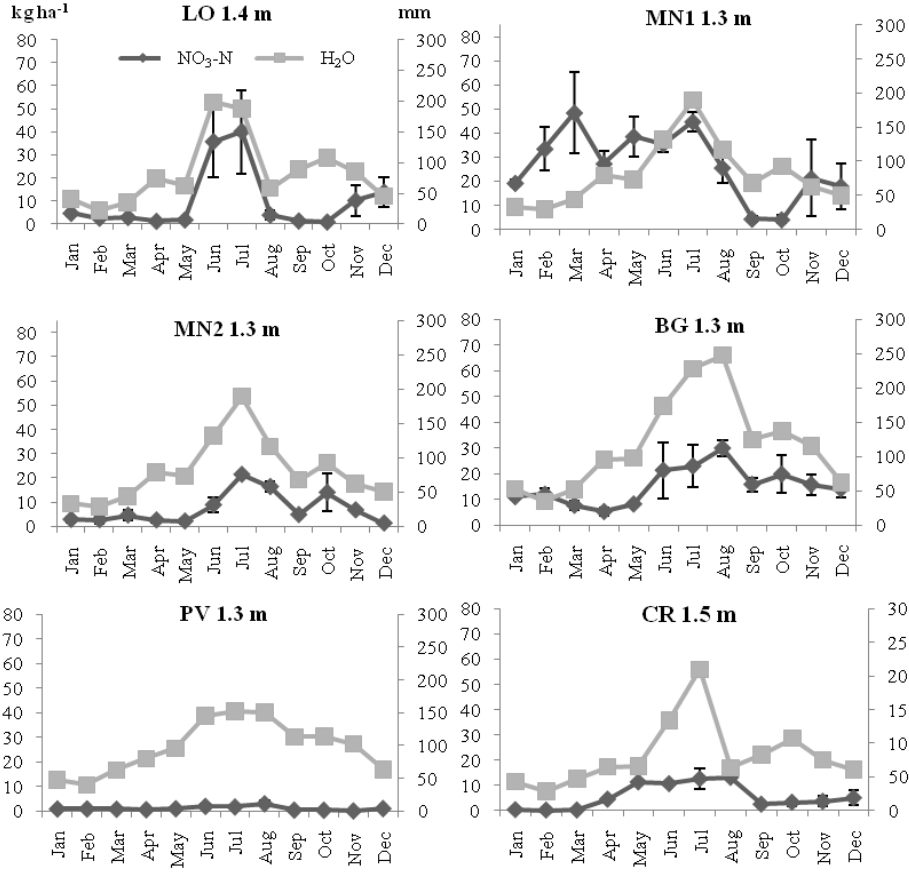


Figure 3.4. Mean monthly nitrate leaching (kg NO_3-N $ha^{-1}month^{-1}$) and water supply (mm, rain + irrigation). Standard deviation: ±.

From January to March lower nitrogen leaching losses were calculated at every monitoring site, with the exception of MN1. This trend is due to the rainfall monthly amount of the same period. The very high level of nitrogen fertilization applied in autumn time at MN1 caused pronounced losses in the first part of the year. At every monitoring site nitrogen leaching occurred during summer reaching remarkable level of 50 kg NO_3-N ha^{-1} month^{-1}. In fact, on June and July irrigation water supply largely exceeded crop evapotranspiration. At MN1, in autumn high losses were also estimated due to the high drainage rate caused by autumn precipitation and eventual organic fertilization .

As reported in Table 3.6, the estimated values of NO_3-N leaching losses were consistent with the calculated difference between N-fertilization amount and crop N-uptake (kg N ha^{-1}year^{-1}).

Table 3.6. Mean annual N-fertilization, crop N-uptake and NO_3-N leaching (kg NO_3-N ha^{-1} year^{-1}), water drainage (mm year^{-1}), drainage NO_3-N concentration (mg L^{-1}year^{-1}).

	N-fertilization	crop N-uptake	NO_3-N leaching	drainage	drainage NO_3-N concentration
LO	343	194	119	539	22
MN1	642	305	321	393	82
MN2	406	289	88	276	32
BG	481	222	184	576	32
PV	314	252	14	112	13
CR	309	222	42	127	33

Once calculated the N surplus as the difference between mean annual N-fertilization and crop N uptake, such surplus was confronted with the estimated value of NO_3-N leaching losses (kg NO_3-N ha^{-1}year^{-1}), year by year at each monitoring site. A significant correlation ($p<0.01$) resulted as shown by regression line value of 0.89 whose slope was 0.83 (Figure 3.5).

At LO NO_3-N mean leaching was 119 kg NO_3-N ha^{-1}year^{-1}. Such value is greater than leaching value scored in 2006 (11 kg NO_3-N ha^{-1}year^{-1}) due to autumn-sown winter wheat to whom only 47 kg N ha^{-1} was applied. As far as MN1 site is concerned, nitrogen leaching estimated value was 447 kg NO_3-N

ha^{-1} in 2004 whereas the mean annual value was 321 kg NO_3-N $ha^{-1}year^{-1}$. Such difference is due to the very high N fertilization amount which was 801 kg NO_3-N $ha^{-1}year^{-1}$ whereas the mean annual N fertilization amount was 562 kg NO_3-N $ha^{-1}year^{-1}$. At MN2, although a small drainage water amount (276 mm $year^{-1}$) took place, large N fertilization supply (406 kg NO_3-N $ha^{-1}year^{-1}$) involved mean nitrogen losses of 88 kg NO_3-N $ha^{-1}year^{-1}$. In the case of BG mean nitrogen leaching was 184 kg NO_3-N $ha^{-1}year^{-1}$ due high rate of percolation together with to the remarkable N fertilization over whole period (481 kg NO_3-N $ha^{-1}year^{-1}$). At PV, substantially small amount of nitrogen losses by leaching was

estimated (14 kg NO_3-N $ha^{-1}year^{-1}$) due to Italian ryegrass as catch crop. At CR site small water drainage amount was calculated (198 mm $year^{-1}$) and only mineral N fertilizer was applied (309 kg NO_3-N $ha^{-1}year^{-1}$); nitrate leaching was 69 kg NO_3-N $ha^{-1}year^{-1}$. Highest values of NO_3-N were scored from May to August due to high mineral N fertilization together with spring rainfall and summer irrigation.

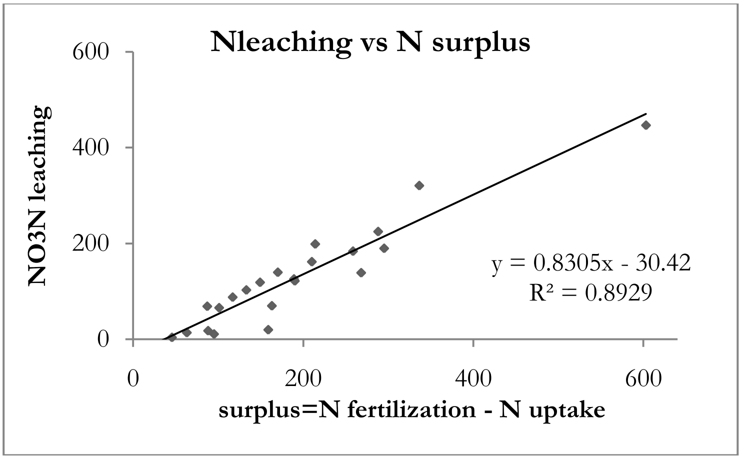


Figure 3.5. Match between calculated N surplus (mean annual N fertilization- N uptake) with mean annual NO_3-N leaching (kg NO_3-N ha^{-1} $year^{-1}$) at every monitoring site.

The mean annual concentrations of NO_3-N in drainage water are reported in Table 3.6. On average values are remarkably high, particularly at MN2. At PV the lowest concentration was scored. Each single annual concentration were close to the mean annual value (maximum value of the between-years coefficient of variation was 24%), with the exception of LO in 2006 (4 mg L^{-1}year^{-1}) where a very low fertilization amount was applied to autumn-sown winter wheat crop.

3.5. Discussion

Nitrogen leaching was strictly affected by N-fertilization amount and crop N removal-uptake, being clearly shown by a close correlation (Figure 3.5). The mean value of crop N-uptake (242 kg N ha^{-1}) suggested the exceeding amount of N-fertilization whose mean value was 416 kg N ha^{-1}, 238 and 178 applied as organic manure and mineral fertilizer, respectively. Grignani and Zavattaro (2000) reported value of N-input under similar cropping systems in Po valley (Piemonte Region) ranging from 369 to 509 kg N ha^{-1}, where calculated surplus was 128 to 335 kg N ha^{-1} year^{-1}. Mantovi et al. (2006) reported a mean annual amount of 475 kg N ha^{-1} as pig slurry in Po valley (Emilia-Romagna Region) under silage maize and other cereals, as grain sorghum and winter wheat, cropping systems. In this case mean calculated surplus was 375 kg N ha^{-1} year^{-1}, and mean crop N removal was 100 kg ha^{-1}.

Calculating the ratio between crop N-uptake and N-input as efficiency index, results were 57, 51, 71, 50, 79, 72 % at LO, MN1, MN2, BG, PV and CR. LO monitoring field was autumn-sown to winter wheat in 2005; in 2006 the efficiency index was pretty high (67%) compared to mean period value of 57%. At MN1 mean value relatively low of efficiency index was due to 24% scored in 2004 when 802 kg N ha year^{-1} was applied and N-uptake was small (198 kg N ha^{-1}). In general, the highest value of efficiency recorded at PV was due to the fertilization management, based on N balance calculation; this approach brought to an application of controlled amount on N fertilizers, with no yield decrease. In particular, very high value of efficiency was scored at PV (87%) in 2009 which was second year of a double cropping systems, as silage maize-Italian ryegrass, due to including of the catch crop.

NO_3-N losses differed over the year; such difference are strictly related to exceeding irrigation water supply. In fact, comparing monthly leaching, remarkable percentage was scored on June, July and partially on August. Maize crop requires high level of water because of its high evapotranspiration (about 550 mm per cropping season) and under Po valley climatic condition maize is not a rain-fed crop. In order to achieve crop water demand, farmers irrigate maize fields typically 3 or 5 times in the case of border irrigation, supplying 80 up to 200 mm on each irrigation event. This procedure causes high rate of percolation, thus a certain amount of nitrogen is lost, being closely subsequent to spring mineral N-fertilization. At studied monitoring sites takes place such phenomenon, with the exception of MN1 and MN2, where sprinkler irrigation is adopted. Here the large amount of NO_3-N losses is due to the very high level of N-input. Summer mean leaching represents 46% of the entire annual losses with minimum value of 33% scored at MN1 and a maximum of 67% at LO. Autumn losses represented 18% on the mean total leaching. At BG site uncorrected irrigation management, together with high N-input, involved 74 kg NO3-N ha-1 of leaching on June, July and August that represented 40% of the entire amount of annual losses, whereas autumn (September, October and November) losses were 51 kg NO3-N ha-1 being 28%. In summer water input, precipitation together with irrigation, was 650 mm and in autumn rainfall was 349 mm. Moreover, since BG soil is characterized by an remarkable stone content (kg kg-1) ranging from 34% to 55% over 1.3 m depth, better irrigation management should be mandatory, as increasing the number of irrigation events of smaller water amount.

Crop type and its management typically affected leaching losses as shown by LO and PV results. It was specially remarkable that including an autumn–sown crop in rotation with maize involves very strong reduction in losses of NO_3-N, as demonstrated by the result of PV. Mean annual leaching was 14 kg NO_3-N $ha^{-1}year^{-1}$due to a very low drainage (112 mm $year^{-1}$). Although at Italian ryegrass sowing mean amount of 210 kg N ha^{-1} was applied, such autumn-sown crop water and N-uptake strongly reduced percolation and nitrogen leaching. At LO in 2006 a substantial decreasing of 71% in autumn-winter nitrogen leaching resulted, relatively to previous annual values. That was due to winter wheat sowing in 2005 after a four years monoculture of silage maize. In summer 2006, after winter wheat harvest on June 27th, low NO_3-N content was recorded (5.5 mg L^{-1} at bottom layer). Moreover, summer nitrogen losses were negligible because of no water irrigation was applied.

Results of annual nitrogen leaching were remarkably different at each site, since soil characteristics strongly affect water dynamics and then drainage amount. Large nitrogen losses were recorded at BG site which is characterized by a very high stone conten*t,* although had a relatively fine texture. LO site has a fine loamy over sandy soil and, together with a relevant nitrogen fertilization amount, had considerable nitrogen losses. But the soil effects seemed to be not so relevant as the effects of management: the soil with the highest clay content (MN1) had the worst values of leaching due to improper nitrogen management.

Crop rotation including autumn-sown crop, as winter wheat and Italian ryegrass allows for smaller nitrogen losses, removing soil nitrogen during autumn rainfall period, characterized by high percolation rate, thus at PV site the smallest nitrate leaching was recorded. Moreover, mean water supply was 240 mm over the summer period. Such value is lower than irrigation amount recorded at the other sites.

In order to assess the potential risk of nitrogen losses by leaching the NO_3-N soil concentration and leaching were studied according to different approaches. Daudén et al. (2004) proposed a relation between drainage NO_3-N concentration (mg L^{-1}) and total inorganic N applied (kg N ha^{-1}), considering mineral fertilization and total ammonia nitrogen in manure (55% of total Kjeldahl nitrogen). Such relation was calculated in the present study obtaining good correlation ($R^2=0.65$, $p<0.01$). The linear relation follows:

$$NO_3Ndrainage = 0.1InorgN + 8.43 \quad [3.2]$$

where NO_3-*Ndrainage* is NO_3-N soil concentration (mg L^{-1}), scored after crop harvest at bottom layer, *InorgN* is the total inorganic N applied (kg N ha^{-1}).

Another relation proposed by Daudén et al. (2004) deals with NO_3-N leaching (kg NO_3-N $ha^{-1}year^{-1}$) and total inorganic N applied. Also in this case statistics indexes indicated significant linear correlation ($R^2=0.47$, $p<0.01$). The linear relation is:

$$NO_3Nlea = 0.26InorgN + 28.32 \quad [3.3]$$

where NO_3-*Nlea* is NO_3-N leaching (kg NO_3-N $ha^{-1}year^{-1}$).

Andraski et al. (2000) proposed a relationship between surplus of N fertilizer applied and end-season soil NO_3-N concentration at bottom layer. Appling such method, relation had good coefficient of correlation ($R^2=0.63$, $p<0.01$).

The linear relation is:

$$NO_3Nsoil = 0.1Nsurplus + 4.86$$

[3.4]

where *Nsurplus* is the exceeding N fertilization (kg N ha^{-1}).

Sullivan and Cogger (2003) suggested a method through which assessment of N management is possible, measuring the soil NO_3-N concentration in post-harvest in the upper 30 cm soil. They categorized soil concentration by 3 cases to which corresponded different advising in N management: (i) post-harvest NO_3-N is less than 20 mg L^{-1}, (ii) post-harvest NO_3-N is 20 to 45 mg L^{-1}, (iii) post-harvest NO_3-N is greater than 45 mg L^{-1}. In the upper 30 cm soil, the mean soil concentration, calculated through years after crop harvest, was 25, 53, 19, 22, 12, 35 mg L^{-1} at LO, MN1, MN2, BG, PV, CR, respectively. Each single annual concentration recorded at sites was close to the mean value. According to the response, strong change in N management should suggest in the case of MN1, avoiding mineral fertilization and reducing manure N application, together with smaller water supply in summer. In the case of LO, MN2, BG and CR a decrease in water supply and sidedress fertilization could reduce N losses. According to this method PV has proper management. The response obtained by applying the methodology proposed by Sullivan and Cogger (2003) is consistent with our N leaching calculation.

3.6. Conclusions

At several sites of the Po Valley, where there is one of the most intensive agricultural areas, lying on one of the biggest European aquifer, nitrogen in form of nitrate in soil solution and leaching was measured at real field scale. The whole set of measurement indicated an high risk of leaching with concentration exceeding the threshold of water drinkability of 50 mg L^{-1} of nitrate, but also showed several possibility to be compliant with Nitrate Directive. Irrigation effect was remarkable in affecting nitrogen leaching. In fact, highest mean monthly nitrogen leaching was recorded in summer time when irrigation supply caused considerable drainage events. In fact, in the case of sprinkler irrigation drainage was lower and nitrate losses could be reduced, avoiding yield losses. The amount of mineral fertilization also caused summer nitrogen leaching. The experimental data set suggest to manage properly irrigation and mineral fertilization in order to reduce nitrogen losses.

Overall results suggested the possibility to use relatively large amounts of organic nitrogen without exceeding threshold risk in several soil type, under the condition to use amount of fertilizer computed on the base of a nitrogen balance, avoiding any leaching due to irrigation in summer. The effect of different type of soil become really relevant only under a management of irrigation based on hydrological balance and rational fertilization.

3.7. Acknowledgements

This study forms part of the regional project ARMOSA, where soil water and nitrate dynamics are measured and analyzed under different cropping systems at real farms' monitoring sites. Such project is currently ongoing and co-ordinated by the Department of Plant Production of the University of Milan, the Regional Agency for Agricultural and Forestry Development of Lombardy Region, the Institute for Mediterranean Agricultural and Forestry Systems - National Research Council of Ercolano, Neaples, and financed by the Lombardy Region since 2002.

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Chapter 4

The ARMOSA simulation crop model: main features, calibration and validation results

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Keywords

Crop growth, nitrogen dynamics, water dynamics, simulation model.

4.1. Abstract

The ARMOSA software is a dynamic simulation model able to simulate crop growth and development, water and nitrogen balance under different pedoclimatic conditions and cropping systems in arable land. ARMOSA implements different approaches in order to ensure accurate simulation of any process related to soil-crop-atmosphere continuum. A large data set from 6 monitoring sites of Lombardia plain was used to calibrate and validate the model parameters. Measured meteorological data, six soil chemical and physical characterizations, observed data of 6 crops (2 silage and 2 grain maize hybrids of different FAO class, winter wheat and Italian ryegrass), management data, such as amount and timing of N fertilization and irrigation, allowed for a proper parameterization. Calculated fit indexes confirmed the reliability of the model in predicting adequately crop-related variables, such as above ground biomass (RRMSE=11.18, EF=0.94, r=0.97), LAI maximum value (RRMSE=8.24, EF=0.37, r=0.72), harvest index (RRMSE=19.4, EF=0.32, r=0.74), and crop N uptake (RRMSE=20.25, EF=0.69, r=0.85). By using two different 1-year data set from each monitoring site, the model was calibrated and validated, getting to good results: RRMSE=6.28, EF=0.52, r=0.68 for soil water content at different depths, and RRMSE=34.89, EF=0.59, r=0.75 for soil NO_3-N content along soil profile. The simulated N leaching was in full agreement with measured data (RRMSE=26.62, EF=0.88, r=0.98).

4.2. Introduction

The prediction of nitrogen amount in groundwater involves knowledge and understanding of nitrogen dynamics within environment components, the chemical form of such element, and the nitrogen cycle and balance in continuum soil-plant-atmosphere (Bergstrom et al., 1991; Acutis et al., 2000).

In order to get a proper evaluation of the nitrogen balance in soil of arable land the analysis of the soil water dynamics and balance has first to be carried out, being water the chief vector of nitrate to groundwater (Rozemeijer et al., 2010; van der Velde et al., 2010). Moreover, a proper evaluation of the soil water content is fundamental in crop yield prediction, since economic production plays a crucial role into an analysis of the actual sustainability of the agroecosystem (Stöckle et al. 1992; Kersebaum, 2007).

The complexity and interaction of physical, chemical and biological processes occurring at different space and time scale involve some difficulties in evaluating water movements in soil. To describe the soil water dynamics physically based differential equations of elevated complexity are employed; that is required if a proper description of water and solutes flow is pursued. In order to solve such algorithms dynamic simulation model can be applied (Jarvis, 1989; Stöckle et al. 2003; Wagehenkel e Mirschel, 2005; Zhang, 2010, Bonfante et al, 2010). Together with the soil water flow analysis, a very detailed understanding of nitrogen dynamics is required in order to define a sustainable management in terms of environment protection, in particular of groundwater quality.

The obtainable data set of field monitoring are fundamental to test and parameterize a simulation model; subsequently, once developed and tested, a robust simulation model can predict nitrogen leaching under field crop production.

The above described complexity of the system shows the opportunity to adopt modelling tools, when strongly based on detailed description of the occurring processes and whose performance is verified by using observed data of high reliability (Kersebaum, 1995; Acutis et al., 2000).

In order to ensure a complete data set able to describe a field scenario of arable system potentially prone to nitrate leaching, different variables have to be observed, such as (i) crop-related variables, (ii) mineral nitrogen content in soil solution, (iii) soil water content, (iv) agronomic management data, (v) soil characterization and (vi) meteorological data.

A minimum data set of crop variables must include phenological stages, total dry matter (above ground biomass), yield, harvest index, LAI maximum value. The mineral nitrogen content can be measured from soil cores or from soil solution sampled by ceramic porous cups. Data of soil water content can be measured by using time domain reflectometry technique (TDR), applying the empirical Topp's formula to the measured soil bulk dielectric permittivity (Robinson et al., 2003) or by the gravimetric method. Agronomic management data deal with sowing and harvest day, fertilization and irrigation amount, type and number of events.

The ARMOSA project (Monitoring network of soil water quality of arable land in Lombardia) was developed, according to the guiding lines of PTUA (Program of water protection and use) of Lombardia Region (northern Italy), in order to define a methodology for the assessment of soil quality and vulnerability with particular attention to water and nutrients dynamics in arable systems.

The main results of such project was the development of a dynamic simulation model whose reliability is guaranteed by a large set of data observed 6 in monitoring sites in farms representing the ordinary pedoclimatic conditions and the cropping systems of Lombardia plain. Average annual rainfall varied from 690 to 1070 mm year^{-1}, and sites' soils were from fine sandy to clay loam. The cropping systems included silage and grain maize (Zea mays L.), winter wheat (Triticum aestivum L., ww), double annual crop rotation of Italian ryegrass (Lolium multiflorum Lam.). Mean N fertilization amounts were 304 to 642, kg N ha^{-1}year^{-1}. Mean water amount which farmers applied per cropping season (from June to August) was 240 to 350 mm year^{-1} (Perego et al., 2011). Since Lombardia Region is characterized by intensive cropping systems, elevated use of production factors is common, namely nitrogen fertilisers and irrigation water. Agricultural production systems are frequently characterized by high N surpluses as quantified in previous studies (Bechini and Castoldi, 2009, Fumagalli, 2009). ARMOSA simulation model has been developed to be applied in such intensive production scenario in order to evaluate the actual vulnerability of groundwater to nitrate leaching from agricultural source, being mandatory for the Nitrate Directive (91/676/CE) compliance.

4.3. Material and methods

4.3.1. ARMOSA model: overview

The ARMOSA crop simulation model was developed subsequently to a first stage related to the choice of the algorithmic frame to implement in its software code. Such model was defined as useful tool in the prediction of nitrogen dynamics in soil-crop-atmosphere *continuum,* providing an evaluation of the impact of agricultural management on shallow and groundwater quality. ARMOSA is a dynamic model and simulates cropping systems with a daily time-step. The software was written using UML (Unified Modelling Language, Rumbaugh et al., 2005) in order to have an explicit definition of the software structure in terms of components and their relation, allowing possibility to easy modify, improve and maintain the software The software is written with an object oriented language, Visual Basic 6.0, and the object structure is produced directly from the UML representation.

The model simulates agro-meteorological variables, the water balance, the nitrogen balance, and crop development and growth. It consists in four components which are: i) a micro-meteorological model that simulates the energy balance, allowing for evapotranspiration estimation, ii) a crop development and growth model that uses global radiation and temperature, iii) a model of the soil water balance, iv) a model of soil nitrogen and carbon balance.

The software simulating the crop growth implemented for the ARMOSA project is based on gross assimilation of CO_2, and on maintenance and growth respiration to get the final net carbon assimilation. This kind of simulation tools are known as the "School of de Wit" crop models (van Ittersum et al., 2003) by the name of the pioneer scientist who founded the first modelling team in Wageningen, Netherlands. Examples of this type of model are SUCROS (Van Keulen et al., 1982) and the derived WOFOST (Van Keulen and Wolf, 1986).

The user can choose the approach to calculate evapotrasnpiration between the one proposed by Penman-Monteith (Monteith, 1965) and the one by Priestley-Taylor (Priestley and Taylor, 1972). The choice is due to the availability of the meteorological variables, being fundamental input data of simulation. Evapotranspiration is calculated as a part of the energy balance a module according to the FAO Irrigation and Drainage paper No. 56 (Allen et al. 1998) can be chosen.

The hydrological model can be alternatively chosen as a physically based approach according to the model based on Richards' equation, which was implemented in the SWAP model (Van Dam et al., 1997; Van Dam e Feddes, 2000) the empirical approach of cascading (Burns et al., 1974).. The hydraulic parameters for Richards' approach are internally estimated from the van Genuchten parameters provided in the soil data base; if van Genuchten parameters are not available, they can be estimated from texture, organic matter and bulk density using pedotransfer function. A specific pedotransfer function for European soils is referred to as HYPRESS (Wösten et al, 1999).

The nitrogen dynamics component was developed on the basis of the existing model SOILN (Eckersten et al., 1996; Larsson et al.,1999) due to its code in which every N-related process is very well detailed, together with a reasonable requirement of input parameters. Further, the nitrogen cycle as proposed in SOILN was already implemented in other simulation model as WAVE

(Vanclooster et al., 1994) and LEACHN (Hutson, 2003). In particular, the latter was applied in Po plain scenario (Acutis et al. 2000), showing a good reliability in simulating the ordinary intensive cropping systems of the studied area.

In order to provide simulated data, ARMOSA model requires input data which represent variables, parameters, coefficients that are part of the code algorithms. The model user can define (i) crop rotation, (i) sowing and harvest time, (ii) time, amount and type of nitrogen fertilizers (iv) time and amount of water irrigation. Further, user can choose the option of the automatic irrigation, defined by water availability threshold below whose value irrigation water is provided to ensure the field capacity content at a defined depth.

As far as crop characterization is concerned, data base includes several tables of crop parameters of (i) growth, consisting in 74 parameters which lead the gross assimilation of CO_2, LAI (leaf area index) and SLA (specific leaf area), stem and root elongation, respiration loss, vernalization, nitrogen dilution curve (ii) development based on GDD (Table 4.1), (iii) coefficients of dry matter partitioning between above and below ground parts of the crop (Table 4.2), (iv) coefficients of dry matter partitioning between leaves, stem and storage. (Table 4.3), (v) Coefficients for the evapotranspiration calculation (FAO56) (Table 4.4) and (vi) Parameters related to crop residuals module (Table 4.5) used in the nitrogen balance component, being specific for each crop and phenological stage.

Pedological parameters, as input data, are included in data base in which, layer by layer, physical parameters, as texture and bulk density, chemical, as organic carbon (kg kg^{-1} soil) and carbon in the stable fraction of organic matter (kg), are reported. Further, parameters related to van Genuchten (van Genuchten, 1980) soil hydrological dynamics, are also reported. Each soil layer is characterized in terms of nitrogen dynamics by its own physical and chemical parameters, which are also reported in data base. Among such parameters, there are descriptor of every N-related process, (i) mineralization, (ii) crop N uptake, (iii) humification, (iv) volatilization, (v) nitrification, (vi) leaching, (vii) denitrification, (vii) wet and dry atmospheric deposition. Moreover, there are parameters used in the calculation of environmental factors impact, as temperature and soil water content, affecting mineralization rate of stable organic matter fraction. For each soil layer there are 3 types of organic pool, which are humus, manure and litter, and 2 inorganic pools, ammonia e nitrate, each one characterized by its own rate of mineralization or transformation. Inorganic fertilization are described by the ammonia and nitrate percentage of the total nitrogen amount, whereas organic fertilizers are characterized by C/N ratio and the percentage of carbon of the two fraction of the organic fertilization pool which are "litter" (if C/N > 10) e "manure" (if C/N < 10)), and by the percentage of ammonia on the total nitrogen amount. In Table 4.5 parameters used in the nitrogen balance model are reported.

ARMOSA model allows for selection of daily outputs for all growth and soil related variables and summary indicators derived from the simulation results e.g. the development stage and biomass of crops, variables of soil water balance, agro-meteorology as well as stress and efficiency indicators, organic C and N, ammonia and nitrate contents, water flux between layers.

Parametro	Descrizione
id_Crop	progressive number of crop
Crop	crop name
Stage	stage name
stage_BBCH	Value of the stage according to BBCH scale (0-100)
GDD_sum	growing degree days to reach the stage from stage before [°C]
Tbase	base temperature of development at the specific stage [°C]
Tcatoff	catoff temperature of development at the specific stage [°C]
Toptmax	maximum optimal temperature of development at the specific stage [°C]
Toptmin	minumum optimal temperature of development at the specific stage [°C]
Leaves assimilation	leaves CO2 assimmilation efficiency (0-1)

Table 4.1. Parameters related to crop development.

Parametro	Descrizione
id_Crop	progressive number of crop
Crop	crop name
stage_BBCH	stage name
FDMshoot	fraction of total dry matter allocated to shoot (0-1)

Table 4.2. Coefficients of dry matter partitioning between above and below ground parts of the crop.

Parametro	Descrizione
id_Crop	progressive number of crop
Crop	crop name
stage_BBCH	Value of the stage according to BBCH scale (0-100)
FMDleaves	fraction of total dry matter allocated to leaves (0-1)
FDMstem	fraction of total dry matter allocated to stem (0-1)
FDMstorage	fraction of total dry matter allocated to storage (0-1)

Table 4.3. Coefficients of dry matter partitioning between leaves, stem and storage.

Parametro	Descrizione
id_Crop	progressive number of crop
Crop	crop name
stage_BBCH	Value of the stage according to BBCH scale (0-100)
kET	crop coefficient between Etpot and Etcrop

Table 4.4. Coefficients for the evapotranspiration calculation.

Parametro	Descrizione
id_Crop	crop number
Crop	Crop
LeavesResidual	% of leaves that remains on the field after harvest
StemResidual	% of stem that remains on the field after harvest
StorageResidual	% of storage that remains on the field after harvest
Kleaf	mineralization rate of leaves d-1
Kstem	mineralization rate of stem d-1
Kstorage	mineralization rate of storage d-1
Kroot	mineralization rate of root d-1
fCleaf	carbon fraction of leale
fCstorage	carbon fraction of storage
fCroot	carbon fraction of roots
fCstem	carbon fraction of stem
CNleaf	CN ratio of leale
CNstorage	CN ratio of storage
CNroot	CN ratio of roots
CNstem	CN ratio of stem

Table 4.5. Parameters related to crop residuals module.

Parametro	Descrizione
kHumus	mineralization rate of humus d-1 7.00E-05
HumiFractionLM	humification fraction of litter/manure
CmicrobEfficiencyL	microbial efficiency in carbon utilization in litter
CmicrobEfficiencyM	microbial efficiency in carbon utilization in manure
dWaterDenitrification	empirical coefficient for denitrification as a function of water content
kHalfSaturationDenitrification	half-saturation constant for denitrification (mg N/L)
kDenitrificationPotential	potential denitrification rate (kgN/ha.d)
MicrobialWaterCoefficient	empirical coefficient of microbial for water
MicrobialSaturation	microbial activity at saturation
MicrobialTemperature	temperature where microbial response to temperature is = 1
MicrobialTemperatureLinear	temperature where microbial response to temperature is linear
kNitrification	specific nitrification rate (d-1)
kVolatilization	specific volatuilization rate (d-1)
NitrateAmmoniumRatio	Nitrate Ammonium Ratio at equilibrium
AtmDryNH4	Atmosfere dry deposition kgNH4/ha d
AtmWetNH4	Atmosfere deposition by rain kgNH4/mm
AtmDryNO3	Atmosfere dry deposition kgNO3/ha d
AtmWetNO3	Atmosfere deposition by rain kgNO3/mm
Q10	Q10 represents the increase in the turnover rate for a temperature increase of 10°C
MicrobialWCbase	lower SWC limit of microbial activity
MicrobialWChigh	lower SWC limit of optimum of microbial activity
MicrobialWClow	high SWC limit of optimum of microbial activity
ThetaDenitrificationLimited	theta threshold below which no denitrification occurs
NavailabilityMax	maximum availability of mineral nitrogen for immobilization and plant uptake (d-1)
kUrea	mineralization of Urea(d-1)
Ncrop	crop n concentration at start
UptakeCoefficient	for diluition curve

Table 4.6. Parameters employed in the nitrogen balance component; such parameters are specific for each soil layer.

4.3.2. ARMOSA model: the crop component

The crop model of ARMOSA model implements STAMINA crop model (Ferrara et al., 2009; Richter et al., 2010), which is based on SUCROS model (Van Keulen et al., 1982). Differences between the STAMINA, as well as ARMOSA, and the SUCROS model are in development, light interception, absorption model, LAI and EAR growth and water stress factor. Similar to SUCROS, ARMOSA cropping system model estimates the photosynthesis for five positions along the vertical profile of the canopy, selected on the basis of Gaussian integration, to obtain an integrated value of photosynthesis of the whole canopy. While SUCROS used only three Gaussian points during the day to approximate light interception our photosynthesis module uses a time step that is the minimum between 2 hours and the simulation time step. Maximum potential photosynthetic rate is a function of CO_2 concentration in the atmosphere. Crop production is simulated under water and nitrogen limited conditions by linking growth to the soil water and nitrogen balance. In the ARMOSA model the effects of water stress are calculated from relative water content in the soil simplifying the original step function proposed by Sinclair (1986) by using logistic function; (Richter et al., 2001). The water stress factor is affecting photosynthesis and root-shoot partitioning. All crop parameters, for all simulated crops and varieties, are provided in an external data base constructed in MS Access format (e.g. crops.mdb), as described in the previous paragraph.

4.3.2.1. Model and general parameterization for crop development

The model calculates the growing degree days (GDD), the development rate (used in the assimilate partition and LAI estimation) and the vernalization factor. BBCH (2001) scale is used to indicate the crop stages. User have to define, for each stage defined in terms of their BBCH value, the GDD requirements and the minimum, optimal minimum temperature, optimal maximum temperature and cut off temperature in the table “Stage Specific” of the crop data base (see above in Table 4.1). While SUCROS2 uses an abstract scale (0-1-2) our model uses the BBCH scale. In ARMOSA model crop development is based on the growth degree days (GDD), calculated applying a trapezoidal rule which is similar to the rule described by Thornley and Johnson (1990). With an appropriate choice of the 4 reference temperatures, it is possible do simulate the development of different crops, that have different reaction to temperature according to their phonological stage, and using almost all methods to calculate GDD that has been validated in bibliography for different crops.

4.3.2.2. Light interception

There are two source of the solar radiation that reaches the ground or the crop canopy: the direct solar radiation and diffuse radiation. The penetration of both direct and diffuse radiation through the canopy layer is affected by the heterogeneous distribution of the leaves and the canopy layer and the canopy geometry relative to solar position. The model separates the canopy in sunlit leaves and shaded leaves. The shaded leaves are reached by diffuse and scattered flux while the sunlit leaves are reached by direct and diffuse flux. For this reason, the cropping system model estimates the CO_2 absorption following the SUCROS2 model modified in the time integration method, that is able to assess this phenomena and it doesn’t use the simpler RUE-based approach. SUCROS2 approach calculates canopy photosynthesis by integrating individual leaf photosynthesis, as a function of the local condition, over the entire leaf canopy. The SUCROS2 model uses an Gaussian integration above the both canopy (5 points) and time (3 points). The cropping system model uses a Gaussian integration above the canopy (5 points)at each meteorological time step (from half hour to two hours). Furthermore our model has two different integration curve, one for crop with leaves insert in a rosette (e.g. sugar beet) and one for crops with canopy more evenly distributed along the vertical profile (e.g wheat).

4.3.2.3. Photosynthesis of C3 and C4 plant in response to increasing carbon dioxide and temperature

After estimating photosynthesis by using SUCROS2 approach, the model estimates the maximum CO_2 absorption (CO_2max) as a function of the air carbon dioxide concentration and the air temperature following the Goudriaan approach (Goudriaan and van Laar, 1994). If CO_2abs is more than CO_2max, the value of CO_2 absorption converted in carbohydrate production is CO_2max. The description of the CO_2max estimation follows. The photosynthesis-light response curve is an upward sloping curve with a saturation level with light. This curve is characterized by three parameters:

- dark respiration rate as an assimilation level (negative) at zero irradiance [μg CO_2 m^{-2} s^{-1}] (C3=50, C4=50)
- initial light conversion factor as a initial slope of the curve [μg CO_2 J^{-1}] (C3=11, C4=14)
- maximum gross assimilation rate [μg CO_2 m^{-2} s^{-1}] (C3=800, C4=1600)

The maximum CO_2 absorption (CO_2max) is a sum of photosynthetic capacity and dark respiration. Maintenance respiration of stem , leaves and storage are also computed in order to obtain the net amount of dry matter allocated to the different parts of the plant.

4.3.2.4. LAI and green area of ears

The simulation of photosynthetic area of leaves and panicles follow the SUCROS2 where the first phase of green surfaces development following the expo-linear function (Goudriaan and Monteith, 1990), till to a LAI in the range 0.5-1 (depending on the crop that is simulated) and after is dependent of the amount of dry matter allocated to leaves multiplied by the specific leaf area. The new value of LAI is the result between the growth rate (GLAI) and the death rate (DLAI). The death rate is a function of age and self shading of the leaves. In the cropping system model it is possible to use a no constant specific leaf area (SLA) using a function, that consider the progressive reduction of SLA during the life of the plants (Wolfe et al., 1998).

4.3.2.5. Modelling drought-response - related parameters and indicators

Our cropping system model likes the drought both as a factor and as a indicator. The factor of water stress (*kws*) is calculated with a daily time step and affects the crop growth simulation. The following processes are affected by the water stress: carbohydrate production, partitioning, evapotranspiration (ET module). Water stress is one of the most important impact factors on crop production and responsible for spatial variability of yields and of the crop failure in the landscape. The function implemented follows the approach generalized by Sinclair (1986) for water and nitrogen uptake of plants. The water stress factor, *kws*, ranges from 0 to 1, 1 being the best condition, 0 is the maximum stress. Richter et al. (2001) used this approach to model canopy dynamics of sugar beet under early and late drought. The *kws* water stress is calculated in soil layers from top to bottom of the root zone as follows:

$$kws = \frac{2}{1 + \exp\left(-WSpar \times AW\right)} - 1 \qquad [4.1]$$

where *AW* is the available water content of the soil [m^3 m^{-3}] and *WSPar* is a parameter of the crop sensitivity read in from crop parameter table.

The effect of water stress on carbohydrate production is simulated considering a reduction of the absorption of CO_2 directly proportional to *kws*, as multiplying coefficient, considering the stomata closure.

The water effect on partitioning is considered reducing the amount of the net carbohydrate assimilation that in condition of no stress is used for the shoot growth, redirecting it to the roots growth only if the actual stage allows the root growth. When the root stops growing there isn't water effect on partitioning.

4.3.2.6. Crop N demand

The crop model estimates the nitrogen demand and the nitrogen stress. The nitrogen availability (NH4ava, NO3ava) is calculated along the soil profile.

$$NH4ava = 1 - \exp(-0.025 \times NH4profile)$$
$$NO3ava = 1 - \exp\,(-0.0275 \times NO3profile) \qquad [4.2]$$

where

NH4profile= amount of ammonia in the soil profile [kg ha^{-1}].

NO3profile= amount of nitrate in the soil profile [kg ha^{-1}].

The potential uptake is calculated at each soil layer in which there is a crop root:

$$PA = \frac{AW}{laynum}$$

$$NH4upPot = 8 \times RL \times PA \times NH4ava$$

$$NO3upPot = 8 \times RL \times PA \times NO3ava$$

$$NuptakePot = NH4upPot + NO3upPot$$

[4.3, 4.4, 4.5, 4.6]

where

AW: soil water availability of soil profile

laynum: number of layer with crop root

RL: factor of root repartition among layer

NuptakePot: amount of potential nitrogen crop uptake [kg ha^{-1}]

Dilution curve parameters are calculated as follows:

$$NmaxEarly = (2aMax)^{-b}$$

$$Ncrit = aCrit \times \left(\frac{DM}{100}\right)^{-b}$$

$$Nmax = aMax \times \left(\frac{DM}{100}\right)^{-b}$$

$$Nmin = aMin \times \left(\frac{DM}{100}\right)^{-b}$$

[4.7, 4.8, 4.9, 4.10]

where aMax, aMin, aCrit, b are input parameters. NmaxEarly, Ncrit, Nmax and Nmin are respectively the early maturity, critical, maximum and minimum N uptake.

Nitrogen demand [N_D, kg N ha^{-1}d^{-1}] is calculated as follows:

$$N\_D = (Nmax - Ncon) \times DM \times 10 + Nmax \times rateDM \times 10 - Nfix$$

[4.11]

where Ncon is crop nitrogen concentration of day before, DM total crop dry matter [g m^{-2}], rateDM new total dry matter [g m^{-2} d^{-1}].

If N_D is lower than NuptakePot potential uptake then the demand is satisfied, else the demand is reduced by same factor (f) among soil layers.

$$f = N\_D/NuptakePot$$

$$NO3\_D = NO3upPot \times f$$

$$NH4\_D = NH4upPot \times f$$

The new crop nitrogen concentration Ncon(i) is:

$$Ncon(i) = Ncon + (N\_D/((DM + rateDM) \times 10))$$

[4.12, 4.13, 4.14, 4.15]

4.3.3. ARMOSA model: the nitrogen component

A brief description of the main N-related process is given in this paragraph. Figure 4.1 shows the logical structure of nitrogen and carbon balance.

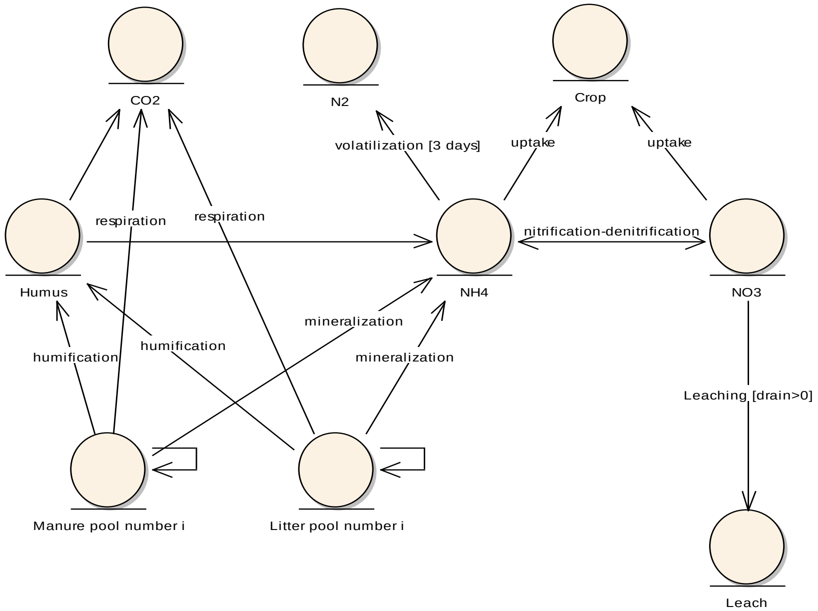

Figure 4.1. Logical structure of nitrogen and carbon balance.

4.3.3.1. Mineralization

The ammonia of manure and litter pools is mineralized as follows:

Nitrogen rate from litter pool to NH_4 pool:

$$NL\_to\_NH4 = -k \times \left(N - \left(\frac{feL \times C}{CNH}\right)\right) \times fT \times fW$$

[4.16]

Nitrogen rate from manure pool to NH_4 pool:

$$NL\_to\_NH4 = -k \times \left(N - \left(\frac{feM \times C}{CNH}\right)\right) \times fT \times fW$$

[4.17]

where fT and fW are temperature and soil water factors, k is the mineralization rate (input parameter, d^{-1}), CNH is the CN ratio of the humus pool, C is the carbon amount of the pool [kg ha^{-1}], N is the nitrogen amount of the pool kgN ha^{-1}, feL is the humification fraction of litter/faeces and feM is microbial efficiency in carbon utilization (input parameters).

The microbial temperature factor fT is:

$$fT = Q^{\frac{T-Tmicro}{10}}$$

[4.18]

Q= input parameter related to pedological features; it is set to 2 [-].

T= it is the actual mean air temperature which is shortened by 2 °C [°C]. T value does not exceed 28 °C.

Tmicro= input parameter below whose value denitrification does not occur [C°].

The microbial water factor (fW) is calculated in each soil layer with a daily time-step as follows:

$$\begin{cases} fW = 0 & if \quad SWC < b \\ fW = \left(\frac{SWC - b}{l - b}\right)^m & if \quad b \leq SWC \leq l \\ fW = fSAT + (1 - fSAT) \times \left(\frac{SWC\_SAT - SWC}{SWC\_SAT - h}\right)^m & if \quad l < SWC \leq h \end{cases}$$

[4.19]

where:

fW= microbial water factor [-].

SWC= actual water content in the soil layer [m^3 m^{-3}].

SWC_SAT = soil water content at saturation [m^3 m^{-3}].

b= lower *SWC* limit of microbial activity [m^3 m^{-3}]; it is calculated as :

$$b = SWC\_base \times SWC\_SAT$$

[4.20]

l= lower *SWC* limit of optimum of microbial activity [m^3 m^{-3}]; it is calculated as:

$$l = SWC\_low \times SWC\_SAT$$

[4.21]

h= higher *SWC* limit of optimum of microbial activity [m^3 m^{-3}]; it is calculated as:

$$h = SWC\_high \times SWC\_SAT$$

[4.22]

SWC_base= input coefficient related to pedological features; it is set to 0.3[-]

SWC_low= input coefficient related to pedological features; it is set to 0.5 [-]

SWC_high= input coefficient related to pedological features; it is set to 0.6[-]

m= empirical water coefficient of microbial mineralization activity [-].

fSAT= microbial water factor at saturation [-].

4.3.3.2. Crop N uptake

Crop preferentially uptakes ammonia, if it is not available then crop uptakes nitrate (Watson, 1986). If available ammonia and nitrate nitrogen do not satisfy crop demand then nitrogen stress occurs. Crop nitrogen uptake occurs along the soil profile investigated by roots.

4.3.3.3. Humification

NH4 content of both manure and litter pools (m. or l.) can be immobilized in the humus pool. Humification occurs if :

$$\frac{1}{CN}-\frac{fe}{CNH}<0 \qquad [4.23]$$

where CN is carbon nitrogen ratio of the pool (m. or l.), CNH is the CN ratio of the humus pool, fe is microbial efficiency in carbon utilization of pool (m. or l.) and is an input parameter.

$$NH4_{imm}=\min\left\{\frac{-k\cdot C\cdot fT\cdot fW\left(\frac{1}{CN}-\frac{fe}{CNH}\right)NH4_{pool}}{NH4_{pool}+NO3_{pool}},\ fN\max NH4_{pool}\right\} \qquad [4.24]$$

where NH4imm is the immobilization NH4 amount [kg ha^{-1}], fT and fW temperature and soil water factors, k is the mineralization rate [d^{-1}] of the pool (m. or l.), C is the pool (m. or l.) carbon amount [kg ha^{-1}], fNmax is maximum availability of mineral nitrogen for immobilization and plant uptake [input parameter, d^{-1}]

4.3.3.4. Volatilization

The amount of ammonia volatilization (*VOL*, kg NH_4^+ ha^{-1} d^{-1}), occurring in the first soil layer, is calculated with a daily time-step as follows:

$$\begin{cases} VOL=-kVol\times SWC\times NH4 \quad if\ DAYS\ \leq VolDays\ and-.5\times SWC\times NH4<-kVol\times swc\times NH4 \\ VOL=\ -.5\times SWC\times NH4 \qquad if\ DAYS\leq VolDays\ and\ -.5\times SWC\times NH4\geq\ -kVol\times sw\times NH4 \\ VOL=\frac{kVOL}{VolFactor}\times SWC*NH4 \quad if\ DAYS>VolDays \end{cases} \qquad [4.25]$$

where:

VOL= the amount of ammonia volatilization [kg NH_4^+ ha^{-1} d^{-1}].

SWC= actual soil water content in the first layer [m^3 m^{-3}].

NH4= actual soil ammonia content in the first layer [kg ha^{-1}].

DAYS = days after fertilization [-].

VolDays= parameter set to 3 (volatilization rate is maximum within the first 3 days after fertilization) [-].

kVOL= volatilization rate [d^{-1}]. It is an input parameter related to pedological features.

VolFactor= reduction factor of *kVOL* when *DAYS* > 3; it is set to 1000 [-].

4.3.3.5. Nitrification

Nitrification occurs if:

$$\frac{NH4 \ - NO3}{NAE} \geq 0$$

then $N\_Nitr = -kNitro \cdot fT \cdot fW \cdot \frac{NH4 - NO3}{NAE}$ [4.26, 4.27]

where *NAE* is the equilibrium nitrate/ammonia ratio (input parameter), *NH4*= actual soil ammonia content [kg ha^{-1}], *NO3*=actual soil nitrate content in the first layer [kg ha^{-1}], N_Nitr=nitrification amount of ammonia [kg ha^{-1}], k*Nitro* is the specific nitrification rate (input parameter, d^{-1}), fT and fW the temperature and water factors.

4.3.3.6. Leaching

The amount of nitrate lost by leaching (*LEA*, kg NO_3^- ha^{-1} d^{-1}) is calculated in each soil layer with a daily time-step as follows:

$$\begin{cases} NO3water = \dfrac{NO3available}{(Wdrain + SWC \times ST) \times 10} \quad and \;\; LEA = NO3water \times Wdrain \times 10 \\ \quad if \; NO3available > 0 \; and \; Wdrain > 0 \\ \\ NO3water = 0 \quad and \;\; LEA = 0 \\ \quad if \; NO3available < 0 \; and \; Wdrain < 0 \end{cases}$$

[4.28]

where:

NO3available= available nitrate content in the soil layer [kg ha^{-1}] when crop N uptake and denitrification loss have been already calculated.

Wdrain= drain water reaching the soil layer [m^3 m^{-3}].

SWC= actual water content in the soil layer [m^3 m^{-3}].

ST= soil layer thickness [m].

4.3.3.7. Denitrification

The amount of nitrate lost by denitrification (*DEN*, kg NO_3^- ha^{-1} d^{-1}) is calculated in each soil layer with a daily time-step as follows:

$$DEN = -kDEN \times fT \times fW \times \frac{\frac{NO3}{ST \times SWC \times 10000}}{\frac{NO3}{ST \times SWC \times 10000 \times HSDEN}}$$

[4.29]

where:

DEN= amount of nitrate lost by denitrification [kg NO_3^- ha^{-1} d^{-1}].

kDEN= denitrification rate [d^{-1}]. It is an input parameter related to pedological features; it is set to 0.2.

fT= soil temperature factor [-].

fW= soil water factor[-].

NO3= actual nitrate content in the soil layer [kg ha^{-1}].

ST= soil layer thickness [m].

SWC= actual water content in the soil layer [m^3 m^{-3}].

HSDEN= amount of nitrate lost by denitrification when soil water content is half of *SWC_SAT* [kg NO_3^- ha^{-1} d^{-1}].

SWC_SAT = soil water content at saturation [m^3 m^{-3}].

4.3.3.8. Atmospheric deposition

Dry and wet atmosphere deposition involve the first layer. Dry deposition is constant while wet deposition is proportional to rain

AtmNH4 = AtmDryNH4 + AtmWetNH4 X rain

AtmNO3 = AtmDryNO3 + AtmWetNO3 X rain [4.30, 4.31]

where:

rain : daily rain [mm]

AtmDryNH4: constant NH_4 deposition [kgNH_4 ha^{-1} d^{-1}]
AtmWetNH4: atmosphere deposition by rain [kgNH_4 mm^{-1}]
AtmDryNO3: constant NO_3 deposition [kgNO_3 ha^{-1} d^{-1}]
AtmWetNO3: atmosphere deposition by rain [kgNO_3 mm^{-1}]

4.3.4. Model calibration and validation

Application of a simulation model without calibration includes not only the risk to fail the observed data (Kersebaum, 1995). Calibration and validation are fundamental procedure to test a set of parameters which can be used in other model applications.

The basic aim of the calibration is to improve the parameters estimation (Jörgensen, 1994) by their adjustment within a reasonable range as indicated by previous research, knowledge or experience.

The model was calibrated using the data sets from monitoring sites, whose characterization and data were reported in *Chapter 3* (Perego et al., 2011). The model was calibrated for maize both silage and grain crops, Italian ryegrass and winter wheat in monitoring sites (Lombardia plain, northern Italy), whose description is given by Perego et al., 2011 (*Chapter 3*).

Data collection included leaf area index, crop biomass and their partitioning into stem, leaf and root four times during the growing cycle and at harvest; dates of 2 phenological stages. A fitting of above ground biomass, LAI maximum value, harvest index and total crop N uptake was calculated employing the whole data set.

Since SWC and soil solution NO_3-N concentrations were measured with high frequency along the soil profile at every monitoring site, the performance of model was tested on such large data of about 3800 data of SWC of soil profile from 0.5 to 1.3 m depth and 1520 data of NO_3-N concentration in soil solution from 0.3 to 1.3 m depth. Such data was obtained averaging values of 3 replicates.

The model was calibrated for a 1-year of data set for each monitoring site, in order to get to a proper evaluation of the model then we validated the model employing a different 1-year data set. The choice of validating models on one year was done to evaluate all simulation on the base of the same period (only for 2 sites more years were available). Table 4.7 reports calibration and validation years and monitoring depths of SWC and NO_3-N.

Table 4.7. Calibration and validation years for each monitoring sites; acquisition depths are also reported.

	calibration year	validation year	depth				
LO	2002	2003	0.3	0.5	0.8	1.2	1.4
MN1	2002	2003	0.3	0.5	0.7	1.0	1.3
MN2	2005	2006	0.3	0.5	0.7	1.0	1.3
BG	2005	2006	0.4	0.7	0.9	1.2	1.3
PV	2006	2008	0.3	0.5	0.8	1.0	1.3
CR	2005	2006	0.4	0.5	0.8	1.0	1.5

We parameterized 6 different crops, the ones sown at our monitoring sites, such as grain maize of 700 FAO class (MG 700), grain maize of 600 FAO class (MG 600), silage maize of 700 FAO class (MF 700), silage maize of 500 FAO class (MF 500), winter wheat (WW) and Italian ryegrass (It.R). Information about agricultural practices, obtained at each sites, helped in choosing the proper crop on the basis of the lasting of the cropping cycle. When similar lasting of two crops was scored, even in the case of crops sown at different monitoring sites, the same crop parameterization was chosen.

As far as crop-related parameters are concerned, basic values for calibration are taken from the parameter set proposed by Van Heemst (1988) for the SUCROS model simulation of grain and silage maize, winter wheat and Italian ryegrass, with the exception of phenological development parameters. In fact in van Heemst phenological parameters were appropriate for crops in northern

Europe but not suitable for mild temperature of our studied area, where GDD sum is higher, as well as cardinal temperature for CO_2 assimilation. Field observation of development stages definitely helped in parameterization of GDD requirement. Other sources of initial values for the parameters were set according to data reported in STAMINA report (Richter et al. 2006) subsequently used by Ferrara et al. (2009) and Richter et al. (2010).

Crop coefficient for ET parameterization were suggested by FAO 56 book.

Parameters related to N dilution curve were set according to Plénet and Lemaire (2000) for grain maize, to Herrmann and Taube (2004) for silage maize, to Justes et al. (1994) for winter wheat; in the case of Italian ryegrass, parameters were derived from the wheat ones.

Parameters of N-related processes were first set using reference data, mainly obtained from literature, searching for experiment data carried out in northern Italy under similar agronomic condition (Grignani et al., 2003).

Hydraulic parameters of van Genuchten curve were obtained by measurements carried out in laboratory on undisturbed soil cores for each monitoring sites (Acutis et al., 2007). A fitting of calculated data of leaching amount at monitoring sites and simulated data was carried out. Leaching losses were calculated as described by Perego et al. (2011, *Chapter 3)* by using the method proposed by Lord and Shepherd (1993).

4.3.5. Evaluation of model performance

The agreement between observed and simulated values was expressed by the indexes proposed by Loague and Green (1991) and more recently discussed by Martorana and Bellocchi (1999) and Fila et al. (2003): the relative root mean squared error, the coefficient of residual mass, the Pearson correlation, slope index and modelling efficiency. For all the indexes O_i is the *i*th observed value, whereas S_i is the *i*th simulated value and n is the number of soil water content pairs. $\overline{O}$ and $\overline{S}$ are the mean of observed and simulated soil water content, respectively.

The relative root mean square error RRMSE (Loague and Green, 1991) has a minimum and optimum value at 0. It is a difference-based measure of the model performance in a quadratic form divided by observed mean, being a relative measure of the fitting. It is calculated as follow:

$$RRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}}}{\overline{O}} \times 100 \qquad [4.32]$$

The coefficient of residual mass, CRM, ranges between −inf and +inf, with the optimum = 0. If positive CRM indicates a good performance of the model, if negative indicates overestimation and when is close to zero indicates the absence of trends:

$$CRM = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} O_i} \qquad [4.33]$$

The coefficient of correlation r (Addiscott and Whitmore, 1987) has its optimum value to maximum (+1) values. Zero means no correlation:

$$r = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(S_i - \overline{S}\right)}{\sqrt{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}\sqrt{\sum_{i=1}^{n}\left(S_i - \overline{S}\right)^2}} \qquad [4.34]$$

The slope quantifies the steepness of the linear regression. It equals the change in S_i for each unit change in O_i.. It is expressed in the units of the S_i divided by the units of the O_i. Slope best value is equal to 1.

$$slope = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(S_i - \overline{S}\right)}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \qquad [4.35]$$

Modelling efficiency (EF) (Nash and Sutcliffe, 1970) can get either positive or negative values, 1 being the upper limit, while negative infinity is the theoretical lower bound. EF values lower than 0 result from a worse fit than the average of measurements:

$$EF = 1 - \frac{\sum_{i=1}^{n}(Si - Oi)^2}{\sum_{i=1}^{n}(Oi - \overline{O})^2} \qquad [4.36]$$

4.4. Results

ARMOSA simulation model showed a good performance in simulating crop-related variables. Table 4.8 reports observed and simulated data of above ground biomass (AGB, kg ha^{-1}) and crop N uptake (kg N ha^{-1}) scored at each monitoring sites. Table 4.9 shows evaluation indexes for different crop-related variables such as (i) AGB, (ii) LAI maximum value, scored at flowering stage, (iii) harvest index, HI, obtained as crop yield and AGB ratio, (iv) crop N uptake.

Different evaluation indexes had scores close to optimal value, especially for AGB and crop N uptake. Although slope values for LAI and HI were not sufficiently close to optimal value, CRM and EF indexes showed a strong reliability of ARMOSA model in predicting data. Fitting was carried out by employing also data observed at flowering stages in order to confirm the good performance of the model over the whole crop development

Table 4.8. Observed and simulated data of above ground dry matter and crop N uptake (kg N ha^{-1}). Acquisition date and standard error (SE) of the observed data are also reported. Grain maize of 700 FAO class (MG 700), grain maize of 600 FAO class (MG 600), silage maize of 700 FAO class (MF 700), silage maize of 500 FAO class (MF 500), winter wheat (WW) and Italian ryegrass (It.R).

			Dry matter			N Uptake			
Site	date	crop	observed	SE	simulated	observed	SE	simulated	time
LO	19/8/02	MF 700	22964	1301	21740	220	33	187	harvest
	5/8/03	MF 700	15508	734	20110	147	32	210	harvest
	19/8/04	MF 700	18747	208	18670	212	18	194	harvest
	7/7/05	MF 700	11157	593	10143	133	14	126	flowering
	17/8/05	MF 700	18415	1041	19110	201	19	224	harvest
	27/6/06	ww	15833	658	13820	190	6	181	harvest
MN1	20/9/02	MG 700	32495	1726	28610	425	43	333	harvest
	7/8/03	MF 700	28037	1042	26450	290	14	262	harvest
	18/8/04	MG 600	20482	1088	21690	198	10	195	harvest
MN2	23/9/05	MG 700	26550	1179	24310	289	25	228	harvest
	5/9/06	MG 700	28123	621	28250	289	18	269	harvest
BG	19/10/05	MG 600	22522	126	22480	197	11	219	harvest
	20/9/06	MF 700	22934	103	21980	236	7	238	harvest
	26/9/08	MG 600	23815	1265	24440	234	24	253	harvest
	25/9/09	MF 700	26454	1078	23890	280	13	251	harvest
PV	6/5/05	It.R	6375	339	6870	84	8	41	harvest
	2/8/05	MF 700	10391	552	10992	153	10	137	flowering
	18/10/05	MF 700	20241	1075	21210	195	22	216	harvest
	11/9/06	MG 700	22764	1209	24600	235	26	188	harvest
	10/5/08	It.R	4997	996	4520	69	6	46	harvest
	25/9/08	MF 500	20993	1115	20620	163	11	280	harvest
	10/5/09	It.R	6703	1548	5950	94	8	51	harvest
	23/9/09	MF 500	21930	1165	20610	222	16	277	harvest
CR	7/7/05	MG 700	14232	756	13323	198	18	198	flowering
	27/9/05	MG 700	27861	145	29950	293	21	302	harvest
	22/8/06	MF 700	16779	653	16630	151	24	144	harvest

Table 4.9. Evaluation indexes of model performance for crop-related variables.

	RRMSE	CRM	r	slope	EF
AGB	**11.18**	**0.01**	**0.97**	**0.94**	**0.94**
LAI	**8.24**	**-0.04**	**0.72**	**0.42**	**0.37**
HI	**19.40**	**-0.05**	**0.74**	**0.59**	**0.32**
N Uptake	**20.25**	**0.03**	**0.85**	**0.83**	**0.69**

As far as SWC and soil NO_3-N, the evaluation of the model performance was carried out by using two different data set in order to first calibrate the parameterization and then validate it.

Results of SWC fitting between observed and simulated values are reported in Table 4.10. The excellent values showed a very good performance of the model at different depths, scoring always positive values in the case of EF index, whose value was often close to 1, which is the optimal value.

The outstanding result was constant fitting values passing from calibration to validation year. In fact no remarkable difference was scored at each monitoring depth and site. In the case of CR the SWC observed data set was not complete and that is way no evaluation was carried out.

Table 4.11 reports the evaluation results of model performance in predicting soil NO_3-N concentration at different depths and sites. Values showed a complete agreement between measured and simulated data with no evident decreasing in model performance from calibration to validation years. Such result confirmed the reliability of the mode. CRM resulted often close to optimal value of 0, whereas EF in every case scored positive value. On average the value of index r was good, although in some cases values lower than 0.6 resulted. In particular, r of the bottom layer at BG had a insufficient value, scoring 0.37 and 0.33 in the calibration and validation year, respectively. Slope values were 0.47 and 0.71, whereas CRM (0.07 and 0.22) and EF (0.21 and 0.19) were good, indicating an overall good performance of the model also in the case of BG at bottom layer.

Table 4.10. Evaluation indexes of model performance in simulating soil water content from 0.5 to 1.3 m depth. Specific acquisition depths are reported.

	LO			MN1			MN2			BG			PV		
	depht	**2002**	**2003**		**2002**	**2003**		**2005**	**2006**		**2005**	**2006**		**2006**	**2008**
RRMSE	0.5	2.68	11.41	0.5	6.94	8.91	0.5	4.00	5.41	0.4	10.17	11.16	0.5	7.11	6.06
	0.8	5.55	9.25	0.7	5.90	6.94	0.7	2.40	2.36	0.7	17.65	16.95	0.8	0.89	1.50
	1.2	1.08	3.21	1.0	5.70	7.98	1.0	3.05	1.18	0.9	4.79	6.80	1.0	7.50	4.39
	1.4	11.67	5.74	1.3	10.35	9.69	1.3	1.30	1.26	1.2	19.64	17.65	1.3	0.71	5.22
CRM	0.5	0.01	0.06	0.5	0.06	0.01	0.5	0.01	0.09	0.4	0.00	0.00	0.5	0.01	0.02
	0.8	0.03	0.08	0.7	0.04	0.06	0.7	0.00	0.00	0.7	0.00	0.01	0.8	0.00	0.01
	1.0	-0.01	0.01	1.0	0.02	0.01	1.0	-0.02	0.00	0.9	0.00	-0.02	1.0	-0.07	-0.05
	1.3	0.03	-0.04	1.3	0.04	-0.04	1.3	0.00	-0.01	1.2	0.03	0.06	1.3	0.08	0.08
r	0.5	0.96	0.64	0.5	0.79	0.43	0.5	0.83	0.69	0.4	0.66	0.54	0.5	0.75	0.76
	0.8	0.45	0.74	0.7	0.91	0.79	0.7	0.67	0.59	0.7	0.75	0.62	0.8	0.46	0.71
	1.0	0.99	0.69	1.0	0.79	0.86	1.0	0.47	0.69	0.9	0.77	0.76	1.0	0.23	0.29
	1.3	0.68	0.69	1.3	0.83	0.78	1.3	0.75	0.40	1.2	0.71	0.71	1.3	0.80	0.69
slope	0.5	0.95	0.54	0.5	0.57	0.51	0.5	1.22	0.92	0.4	0.79	0.41	0.5	0.63	0.62
	0.8	0.52	1.17	0.7	1.11	0.57	0.7	1.02	0.84	0.7	0.98	1.45	0.8	0.35	0.49
	1.0	1.05	0.63	1.0	0.74	0.61	1.0	0.70	0.60	0.9	0.77	0.65	1.0	0.23	0.29
	1.3	0.68	0.69	1.3	0.53	0.77	1.3	1.00	0.37	1.2	0.49	0.49	1.3	0.46	0.41
EF	0.5	1.00	0.77	0.5	0.56	0.23	0.5	0.22	0.01	0.4	0.41	0.25	0.5	0.35	0.28
	0.8	0.42	0.99	0.7	0.55	0.56	0.7	1.00	1.00	0.7	0.24	0.38	0.8	1.00	0.98
	1.0	0.97	0.30	1.0	0.45	0.49	1.0	0.07	0.42	0.9	0.53	0.51	1.0	0.83	0.92
	1.3	0.37	0.52	1.3	0.33	0.22	1.3	0.25	0.09	1.2	0.43	0.70	1.3	0.56	0.46

Table 4.11. Evaluation indexes of model performance in simulating soil NO_3-N concentrations from 0.3 to 1.5 m depth. Specific acquisition depths are reported.

	LO			MN1			MN2			BG			PV			CR		
	depht	2002	2003		2002	2003		2005	2006		2005	2006		2006	2008		2005	2006
RRMSE	0.3	21.11	70.00	0.3	17.41	43.61	0.3	84.35	69.44	0.4	46.98	15.68	0.3	17.55	67.82	0.4	23.47	5.19
	0.5	20.17	35.45	0.5	17.46	26.20	0.5	58.60	57.42	0.7	56.06	23.42	0.5	19.42	69.01	0.5	22.68	10.87
	0.8	18.09	21.41	0.7	34.34	50.59	0.7	22.05	15.69	0.9	81.00	69.00	0.8	18.45	49.51	0.8	29.02	30.57
	1.2	20.20	33.95	1.0	30.34	32.75	1.0	19.80	13.91	1.2	28.83	27.99	1.0	30.90	48.81	1.0	44.77	41.99
	1.4	16.84	38.67	1.3	30.84	34.29	1.3	28.02	1.84	1.3	64.60	40.32	1.3	40.63	19.29	1.5	31.65	32.87
CRM	0.3	0.25	0.25	0.3	0.03	0.12	0.3	-0.18	0.21	0.4	0.04	0.03	0.3	0.08	0.46	0.4	0.13	0.11
	0.5	0.06	0.15	0.5	0.19	-0.09	0.5	-0.20	0.02	0.7	0.28	0.40	0.5	0.27	0.64	0.5	0.09	0.21
	0.8	-0.03	0.07	0.7	0.10	-0.03	0.7	0.14	0.11	0.9	0.16	0.52	0.8	0.12	0.47	0.8	0.16	0.03
	1.2	0.45	0.17	1.0	0.24	0.00	1.0	0.35	-0.07	1.2	0.18	0.08	1.0	0.41	0.19	1.0	-0.01	-0.01
	1.4	0.39	0.20	1.3	0.14	0.07	1.3	0.11	0.04	1.3	0.07	0.22	1.3	0.00	0.70	1.5	0.01	0.01
r	0.3	0.74	0.70	0.3	0.62	0.55	0.3	0.74	0.76	0.4	0.73	0.57	0.3	0.69	0.73	0.4	0.65	0.50
	0.5	0.95	0.67	0.5	0.75	0.91	0.5	0.70	0.71	0.7	0.84	0.64	0.5	0.59	0.90	0.5	0.74	0.85
	0.8	0.78	0.82	0.7	0.62	0.72	0.7	0.75	0.69	0.9	0.76	0.59	0.8	0.44	0.94	0.8	0.96	0.97
	1.2	0.93	0.85	1.0	0.83	0.70	1.0	0.77	0.99	1.2	0.76	0.85	1.0	0.49	0.49	1.0	0.94	0.85
	1.4	0.88	0.82	1.3	0.72	0.90	1.3	0.77	0.82	1.3	0.37	0.33	1.3	0.55	0.94	1.5	0.68	0.87
slope	0.3	0.52	0.72	0.3	0.70	0.34	0.3	0.58	0.55	0.4	0.73	0.57	0.3	0.69	0.68	0.4	0.50	0.50
	0.5	0.68	0.49	0.5	0.64	0.70	0.5	0.54	0.55	0.7	0.84	0.64	0.5	0.59	0.90	0.5	0.85	0.85
	0.8	0.77	0.73	0.7	0.62	0.65	0.7	0.70	0.72	0.9	0.72	0.60	0.8	0.44	0.93	0.8	0.97	0.97
	1.2	1.08	1.17	1.0	0.70	0.97	1.0	0.41	0.40	1.2	0.74	0.85	1.0	0.49	0.44	1.0	0.77	0.85
	1.4	0.98	1.06	1.3	0.85	1.43	1.3	0.85	0.70	1.3	0.47	0.71	1.3	0.55	0.94	1.5	0.68	0.71
EF	0.3	0.33	0.38	0.3	0.10	0.24	0.3	0.50	0.43	0.4	0.44	0.16	0.3	0.44	0.17	0.4	0.21	0.22
	0.5	0.85	0.46	0.5	0.25	0.79	0.5	0.42	0.47	0.7	0.39	0.18	0.5	0.68	0.15	0.5	0.45	0.55
	0.8	0.57	0.73	0.7	0.13	0.47	0.7	0.38	0.29	0.9	0.24	0.16	0.8	0.77	0.69	0.8	0.94	0.93
	1.2	0.30	0.28	1.0	0.10	0.05	1.0	0.74	0.65	1.2	0.23	0.61	1.0	0.58	0.21	1.0	0.33	0.46
	1.4	0.31	0.23	1.3	0.11	0.25	1.3	0.39	0.22	1.3	0.21	0.19	1.3	0.30	0.39	1.5	0.71	0.75

Another interesting match dealt with the performance of the model in predicting nitrogen leaching in form of nitrate. Perego et al. (2011, *Chapter 3*) reported results of nitrogen leaching, obtained by measuring NO_3-N concentration in soil solution and then calculating leaching as proposed by Lord and Shepherd (1993). Therefore, a fitting between calculated and simulated data was tested. The fitting was carried out by employing annual leaching data of monitoring sites. Monitoring years were 21, adding every year of the all sites. The results of the match was excellent, scoring values of evaluation indexes close to optimal values: RRMSE=26.62, CRM=-0.06, r=0.98 , slope=1.24 and EF=0.88. CRM, whose value was negative, although close to zero, indicated a slightly overestimation of the model in simulating nitrogen leaching. Figure 4.2 shows the linear regression of leaching data. The calculated slope differ statistically to 1 ($p<0.05$) which is the best obtainable value. When 2004 N leaching in MN1 was not included in the regression analysis, then slope value got a better value which did not statistically differ from the best score 1 ($p>0.05$).

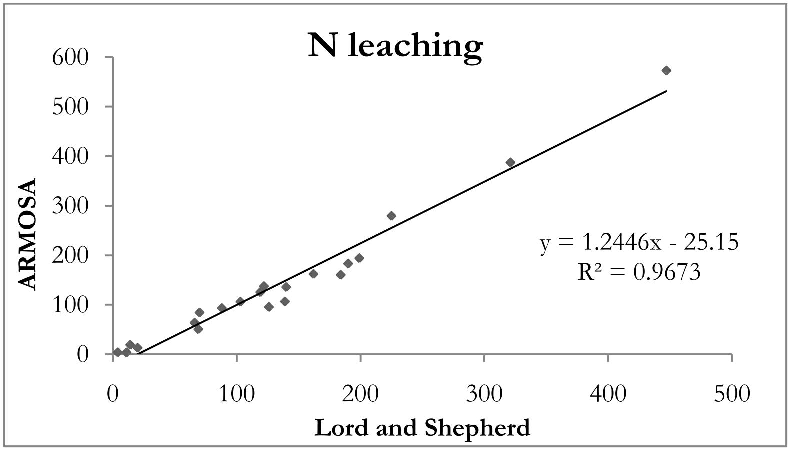

Figure 4.2. Regression line of nitrogen leaching data.

4.5. Discussion

The calculated fit index confirmed a remarkable model performance in predicting above ground biomass, crop N uptake, soil water content, soil NO_3-N concentration at different layers, and N leaching. Existing modelling calibration carried out under similar condition gave same or even worse results, compared to the ARMOSA model performance.

Bechini et al. (2006) parameterized CropSyst model (Stöckle et al., 2003) for winter wheat crop by using data set of four monitoring sites in Lombardia plain. Among the reported fit indexes RRMSE (9 to 32) , EF (0.57 to 0.98), slope (0.61 to 1.09), r (0.89 to 0.99) were in agreement with the one we calculated for AGB. Also for crop N uptake fit indexes were in agreement being RRMSE 8 to 28, EF -0.29 to 0.95, slope 0.32 to 1.04, r 0.5 to 0.99.

Fernandez et al. (2002) evaluated the WAVE 2.1 (Vanclooster et al., 1996) and the EURO-ACCESS-II (Armstrong et al., 1996) models soil water content in a cropped soil under Mediterranean conditions; average EF was equal to -6 and -3.5 during the model calibration and validation, respectively. Bonfante et al. (2010) compared SWAP (Van Dam et al., 1997), CropSyst (Stöckle et al., 2003) and MACRO (Larsbo and Jarvis, 2003) models to predict soil water content under a maize cropping systems at two sites in Lombardia plain. EF was -0.45 to 0.42, r was 0.39 to 0.79, whereas CRM value was always close to zero.

Kersebaum and Beblik (2001) evaluated HERMES (Kersebaum, 1995) in predicting mineral nitrogen content in the root zone on single fields (A) of a water catchment in Germany and their average values separated for cropping systems (B). In A comparison r and slope resulted 0.54 and 0.64, whereas in B comparison r and slope were 0.87 and 1.24.

Under maize cropping systems in Po valley, Morari and Giupponi (1997) estimated N leaching by using the GLEAMS (Arnold et al., 1990). The comparison between observed and simulated data had a R^2 of 0.913 and slope 0.82.

4.6. Conclusions

In order to assess the actual nitrogen losses due to leaching phenomena in Po Valley a project called ARMOSA has been formulated. The ARMOSA model has been developed as a dynamic, daily time step, cropping system simulation model to estimate water and nitrogen dynamics. In particular, all N-related processes are simulated with high accuracy. Data collected allowed for the calibration and validation of the ARMOSA model simulating the N-cycle for the Lombardy environment, hydrological dynamics and cropping systems, using as input data measured daily weather data (maximum and minimum air temperatures, global solar radiation, and precipitation), soil layers and crop parameters, agronomic and topographic information.

The evaluation results confirmed the reliability of the model in predicting adequately (i) crop-related variables, such as above ground biomass, LAI maximum value, harvest index, N uptake, (ii) soil water content at different depths, (iii) soil NO_3-N content along soil profile, (iv) nitrogen leaching.

The use of ARMOSA shows that N application amount is only one of the concurring elements controlling the amount of N leaching. The crop rotation seems to be the main factor determining N leaching. Permanent and managed grassland, characterized by a long cycle and a good N uptake, are the more protective cropping systems, whilst introducing the wheat in crop rotation generally increased the leaching. Also soil hydrological properties in interaction with water amount from rain and irrigation seem to be a relevant parameters controlling leaching. Consequently, optimization of N application in term of amount and dates, seem to be to assess at very detailed time and space scale, on the basis of cropping system, soil and meteorological conditions.

The ARMOSA model appeared to be a useful tool in evaluating actual agricultural management in terms of productivity and environmental impact in arable land. Future model application could help in defining alternative N fertilization management under different pedoclimatic condition in order to find a proper combination of production factors able to improve the agroecosystem quality.

Chapter 5

Regional application of the ARMOSA model to estimate nitrogen leaching under different agriculture management of intensive cropping systems

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Keywords

cropping systems, agricultural management, nitrogen fertilization, nitrate leaching

5.1. Abstract

The aim of this work was an evaluation of alternative management under different cropping systems scenarios by applying the ARMOSA crop simulation model.. The model run over 20 years (1988-2007) in 35 simulation units, obtained by dividing Lombardia plain in homogenous districts in terms of pedological, climatic and cropping systems features and divided in Nitrate Vulnerable Zones (NVZs, 22 districts) and non-Nitrate Vulnerable Zones (nNVZs, 13 districts). Each district was characterized by (i) two representative soil types, (ii) a meteorological observed data set, (iii) crop rotations according to the regional land use analysis, (iv) organic N load, calculated on the basis of livestock density. We defined 3 scenario for districts laying in NVZs: (i) an hypothetical scenario with no limitation in organic N application (AC), (ii) an hypothetical scenario compliant with the mandatory threshold of 170 kg organic N ha^{-1} year^{-1} (ON170), (iii) a scenario in which N organic threshold was enhanced to 250 kg N ha^{-1} year^{-1} (ON250). In the case of nNVZs only the AC scenario was simulated. Comparing the ON170 to AC scenario, ON170 had lower leaching, being strongly reduced the total N amount. Evaluating simulated data of crop yield and nitrogen leaching, ON250 scenario appeared to be more sustainable then AC scenario in economic and environmental terms, although higher N organic input, because of no autumn manure spreading, catch crops and reduced mineral N fertilization.

5.2. Introduction

The European Nitrates Directive 91/676/EEC allows for the possibility for a derogation in respect to the maximum amount of 170 kg N ha^{-1}year^{-1} for livestock manure, if it is demonstrated that the Directive's objectives are still achieved and that the derogation is based on objective criteria such as long growing seasons, crops with high nitrogen uptake, or soils with a high denitrification capacity (European Commission Report, 2010). To avail of the derogation Member States must (i) apply to European Commission providing scientific case meeting requirements laid out in Directive, (ii) have a compliant Action Programme in place, (iii) must receive majority vote of other Member States at EU Nitrates Committee. A derogation asked by Italy Government is currently under revision by the EU Nitrate Committee for the Italian Nitrate Vulnerable Zones (NVZ). The request is to enhance the N fertilization as organic manure from 170 to 250 kg N ha^{-1} $year^{-1}$ in NVZs in regions of Lombardia, Piemonte, Veneto, Emilia-Romagna and Friuli-Venezia-Giulia.

The revised Action Programmes of the five regions applying for derogation, in case derogation request were approved, will contain two main additional measures related to N management: (i) the autumn distribution of manure will be gradually reduced, in order to achieve a higher Nitrogen Use Efficiency (NUE), (ii) derogation farms are required to improve manure management increasing the NUE up to at least 65% when applying animal manure: this is one of the stricter mandatory measures to be applied in order to balance the environmental effects of application of a higher amount of organic nitrogen. In order to achieve the 65% minimum threshold of NUE it is required to increase the cropping season over the year, including autumn-sown crop and summer herbage, after maize (Zea mayze L.) and winter wheat (Triticum aestivum L.) harvest, respectively.

The designation of Nitrates vulnerable zones in Italy falls under the competence of Region Government. Designation, which took place in the late nineties, has been enlarged between 2006 and 2008; it is based on the criteria set out in article 3 and Annex 1 of nitrates directive, on the basis of the results of monitoring programmes assessing nitrate concentration in surface and groundwater and trophic status of surface waters. In Lombardia designated NVZs represent approximately 67% of the utilised agricultural area (UAA) in Northern Italy. In detail the percentage of NVZs over the UAA exceeds 80%

in Lombardia, whereas NVZs represent 56% of the regional plain areas (Regione Lombardia, 2006a). In plain area of Lombardia (from 44°50'N to 45°50'N and from 8°40'E to 11°80'E), UUA is about 790,000 ha and the main cropping systems are maize-based (Bechini and Castoldi, 2009; Fumagalli, 2009). Such crops have a relative high N requirement and a potential N uptake which allow for elevated N input up to 300 kg ha^{-1}. Farming systems in the plains of the region are strictly linked to livestock type: i) dairy and beef cattle (2,000,000 units) and ii) pig (4,080,000 units) (ISTAT, 2010b). The average nitrogen load from livestock is about 172 kg N ha^{-1}. In the western area where cereal farms are predominant, the average nitrogen load is low (from 30 to 90 kg ha^{-1}) whereas in the central and eastern parts the presence of livestock farms (mainly dairy, cattle and swine) determines high nitrogen loads (from 190 to 350 kg ha^{-1}) (Regione Lombardia, 2006b). Such high livestock density involves high availability of N manure but also serious problems related to manure stock and disposal.

In Lombardia two irrigation methods are adopted. In western plain border irrigation is mostly used, whereas in the eastern part farmers commonly carry out sprinkler irrigation (Facchi et al., 2005). The number of irrigation events depends on the irrigation method, soil and the cropping system. In the case of sprinkler irrigation events are 4 to 7 per year with an average amount of irrigation water of about 45 mm, whereas border irrigation has small efficiency that is why mean water mean amount is 80 mm, where irrigation events are 3 to 6. The less available is the water the more frequent is sprinkler irrigation instead of surface irrigation.

According Brunetti et al. (2009a) for a standard period (1961-1990), average annual temperatures of 12 to 14 °C are recorded in Lombardia plain, where average annual rainfall is 915 mm year-1 (Brunetti et al. 2009b). Maximum rainfall, above 100 mm month^{-1} are recorded in late spring (May-June) and

Autumn, while colder months of January and February also record relatively low precipitation, less than mm month^{-1}.

Soils of Lombardia plain have medium to low organic matter (OM) content. (Monaco et al., 2008). The mean topsoil organic carbon (OC) content resulted 1.2%. Summer high temperature contributes to enhance the mineralization rate, leading to a reduced fertility status (Monaco et al., 2009). Management practices through application of exogenous organic matter, such as livestock manure and compost, could help in counteracting OM decline induced by natural factors, such as climate and soil parent material and by land use.

In Lombardia the percentage of soils in NVZs per texture classes are (i) 4% for soil with sand > 60%, (ii) 93% for soils with sand < 60% and clay < 35%, (iii) 3% for soils characterized by a clay content > 35% (Calzolari et al., 2001).

Over the last decade, results in measurements carried on Lombardia watertable showed a slightly reduction in nitrate concentration (mg L^{-1} NO_3). Regional Environmental Agency (ARPA) monitored nitrate in groundwater in 335 wells. Well depth ranges from 2 to 40 m, while the depth to the bottom of the screen level from 12 to 25 m; all wells are within the unconfined aquifer. Average of measured concentrations of the whole regional area was 18.3 over the period from 2002 to 2005, and 17.4 mg NO_3 L^{-1} from 2006 to 2008. Over such two periods NO_3 concentration (mg NO_3 L^{-1}) was 21.4 in 2002-2005 and 20.9 in 2006-2008 in NVZs, whereas in nNVZs was 14.6 and 13.3 mg NO_3 L^{-1}.

In such contest alternative cropping systems and agricultural management could represent an opportunity to reduce nitrate leaching, avoiding any economic decrease in crop yield. The aim of this work was to evaluate nitrate leaching under 3 alternative scenarios of cropping systems by applying ARMOSA simulation model (Acutis et al., 2011, *Chapter 4*) in the entire plain area of Lombardia region. One of the studied scenarios was defined according to the outline of the intended request for derogation from Italian Government.

A detailed description of the scenarios are reported in paragraph 4.3.2.2.

5.3. Materials and methods

The ARMOSA model run over a period of 20 year using a set of daily meteorological data (1988 - 2007) of the closest weather station available for each district. evaluating nitrate leaching under alternative cropping systems in Lombardia plain, divided in 35 districts. Thus, in each district the effects of different management practices on crop production and N leaching were evaluated and compared for three scenarios, under two representative pedological conditions. A detail section of the simulated cropping systems under the three scenarios is reported in subsequent paragraphs.

5.3.1. District definition

Firstly the agricultural area Lombardia plain was divided into homogenous areas (districts) that are similar for pedo-climatic characteristics and agricultural management practises. Since the ARMOSA represents an utilizable decision tool at local scale, municipality borders were taken into account in order to assess N leaching losses at studied local area. In terms of modelling application, each individuated district represents a simulation unit. The obtained districts were 35, among which 22 and 13 lay in NVZs and nNVZs, respectively. Districts n. 2, 10, 11, 12, 13, 16, 17, 18, 19, 21, 22, 23, 24, 25, 26, 27, 28, 31, 32, 33, 34, 35 are in NVZs, whereas districts n. 1, 3, 4, 5, 6, 7, 8, 9, 14, 15, 20, 29, 30 are in nNVZs. Figure 5.1 shows the 35 districts with regard to NVZs and nNVZs.

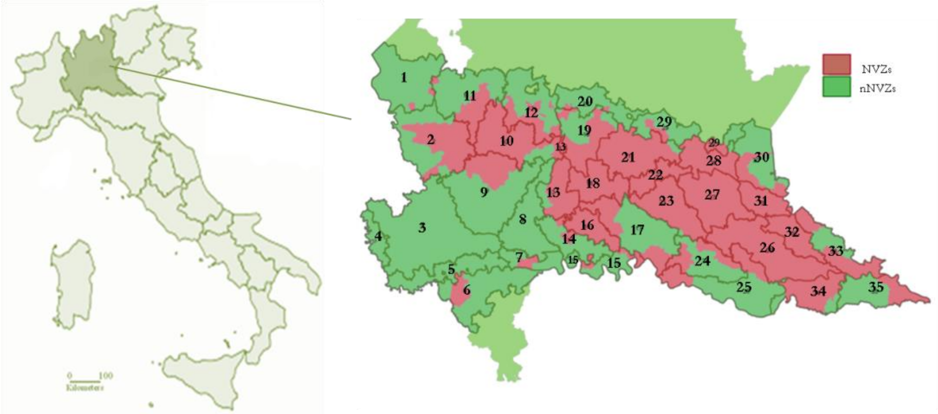


Figure 5.1. Italy and Lombardia. In Lombardia 35 districts are presented; in particular, designated Nitrate Vulnerable Zones (NVZs) are reported in red.

5.3.1.1. Soil and climate

Within each district representative soils were individuated by using the Regional Pedolological Map (Regione Lombardia, 2009). By calculating a 2-step cluster analysis (package SPSS.18), two soils resulted representative for the entire area of each district, with the exception of 6 districts characterized by only one soil, being wide spread over the entire district area. The ARMOSA model database includes pedological characterization of the districts soil, then data were used as model input in this regional application. Figure 5.2 shows the definition of such soils according their texture classes.

Meteorological data were provided by meteorological station present in each district. Such meteorological stations belong to the Regional Network Service. Meteorological variables, daily observed over the period of 1988-2007, were maximum and minimum value of temperature (°C), rainfall (mm). Solar radiation was estimated by using the Hargreaves equation (Hargreaves and Samni, 1985).

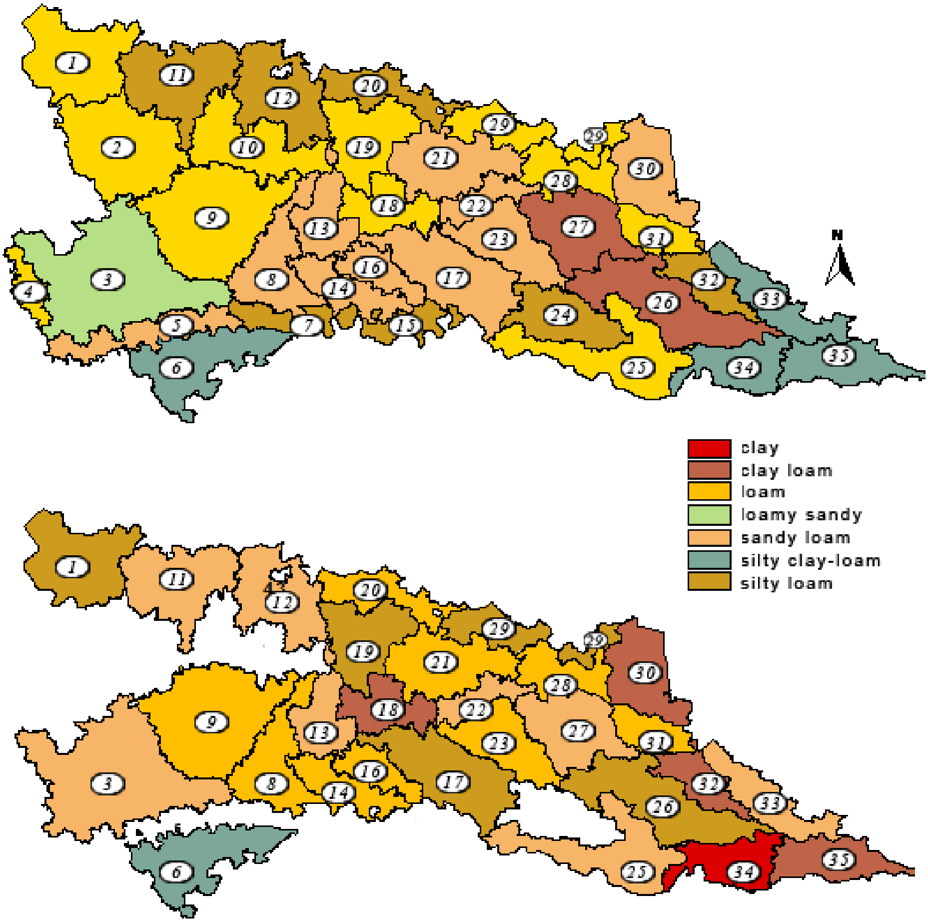


Figure 5.2. Soils texture classes of the two representative soils of each district. As shown, 6 districts are characterized by only one soil.

5.3.2. Scenario definition

The 35 districts insist alternatively in NVZs or in nNVZs, as designated by Lombardia Government. The modelling analysis operated by using the ARMOSA model consisted primarily of the scenarios definition. In order to test different agriculture management three scenarios were defined: (i) the hypothetical scenario with no limitation in organic N application (AC), (ii) the hypothetical scenario ON170, in which the threshold of N fertilization from manure is set on 170 kg N ha^{-1}year^{-1}, (iii) the ON250 scenario, defined according to the outline of the requested derogation of, in which the N input is enhanced from 170 to 250 kg N ha^{-1}year^{-1}, and mineral N fertilizers amount decreases according to crop N requirement. ON170 and ON250 scenarios were tested only in districts laying in NVZs, because evidently nNVZs do not require any alternative management. ON170 differs from AC in terms of N organic fertilization. As suggested by its name, the ON170 scenario is not currently adopted by farmers, although it is mandatory to be compliant with EU Nitrate directive. Chief differences from AC to ON250 consist of (i) higher N organic, (ii) avoiding manure application on bare soil, (iii) crop rotations including catch crops. Particularly, ON250 was defined (i) by introducing new crops in the rotation with the aim of further reducing N losses and maintain economic profitability (ii) reducing the N applied from chemical fertilizers. In fact, several experimental findings (Borin et al., 1997; Morari and Giupponi, 1997; Acutis et al., 2000) confirmed high losses via leaching when elevated mineral N amount was applied. The introduction of a double cropping system is promoted in agriculture because the autumn-winter crops are able to uptake the residual soil mineral N (Thorup-Kristensen, 2001; Kramberger et al., 2008; Trindade et al., 2008), to reduce potential nitrate leaching. In fact, one of the main factors determining the amount of leached N into ground water is the presence of a plant cover (Di and Cameron, 2002) which depletes the soil of mineral N by taking it up and consequently decreasing its leaching (Kramberger et al., 2009). Moreover, the double cropping system provides additional feedstock for livestock utilisation (Fumagalli, 2009).

Details in rotation description and N fertilization management are reported in paragraphs 5.3.2.1. and 5.3.2.2., respectively.

5.3.2.1. Crop rotation

Representative rotations were individuated for each district according to the Regional land use (Regional data base SIARL, 2003-2007). The studied area was restricted to the Utilizable Agricultural Area (UAA) and herbaceous crops as cereals, herbages, meadows, and forage leguminous, being the only type of plants which can be manured. Rotations were taken into account when crop land resulted > 5% UAA. The individuated rotations were aggregated and then expressed in terms of percentage on the total UUA.

The fundamental crop in Lombardia plain is definitely maize so that it was prevalent in defined rotations. Crops mostly planted in the studied area were grain and silage maize, winter wheat, alfalfa (Medicago sativa L.), and meadows Figure 5.3 shows rotations representative of the actual districts' land use.

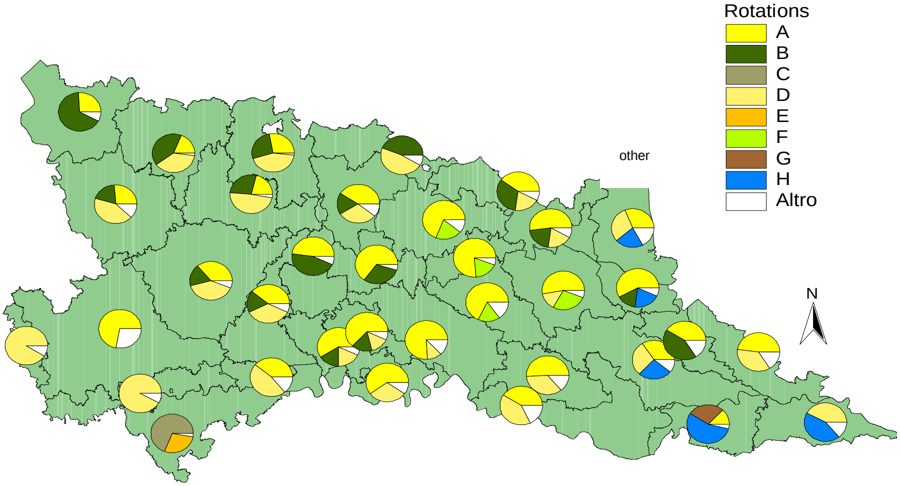


Figure 5.3. Different rotation representative of the actual districts' land use. A=maize monoculture, B=permanent meadow, C= alfalfa-grain maize-winter wheat, D= maize-wheat, E=wheat monoculture, F=maize-meadow, G=alfalfa-wheat, H=alfalfa-maize.

Within any district, the relative area devoted to maize crop includes both grain and silage maize. In the case of ON250 scenario, in some districts where organic N load was particularly high and maize was the predominant crop in terms of relative area, rotation L, as double crop rotation of silage maize of FAO class 500 and Italian ryegrass (Lolium multiflorum Lam.), was introduced among the pre-existing rotations in 19 districts.

In AC and ON170 scenarios the D rotation included grain maize and winter wheat. In ON250 scenario D rotation was modified by introducing a summer herbage of foxtail millet (Setaria italica L.) after winter wheat harvest, in order to ensure crop N up take in summer. Moreover, rotation G was modified in scenario ON250 by introducing an herbage of foxtail millet after wheat harvest. In Table 5.1 the structure of each simulated rotation are reported.

Table 5.1. Crop rotation simulated in studied area under AC, ON170 and ON250 scenarios. The number of crop occurrences in 5-years rotation is shown in brackets.

scenarios	rotations	Crops
AC, ON170, ON250	**A**	**monoculture of FAO 600 maize(5)**
AC, ON170, ON250	**B**	**permanent meadow(5)**
AC, ON170, ON250	**C**	**alfalfa(3) - grain maize(1) - winter wheat (1)**
AC, ON170, ON250	**D**	**grain maize(3) - winter wheat(2)**
AC, ON170, ON250	**E**	**monoculture of winter wheat(5)**
AC, ON170, ON250	**F**	**grain maize(3) – meadow(2)**
AC, ON170, ON250	**G**	**alfalfa(3) - winter wheat(2)**
AC, ON170, ON250	**H**	**alfalfa(3) - grain maize(2)**
ON250	**L**	**FAO 500 maize(5) - Italian ryegrass(5)**

In order to simulate the studied rotation, we used calibrated values of crop parameters of maize, wheat and Italian ryegrass (Acutis et al., 2011, *Chapter 4*). In particular, for maize was used a parameterization for a FAO 600 hybrid which generally reaches physiological maturity over a period of 150 days. Meadows were parameterized starting from values reported by van Heemst (1988); then parameters were adapted according to existing studied carried out in Po plain (Sacco et al., 2003; Grignani et al. 2003). Parameterization of alfalfa were carried out according to Confalonieri and Bechini (2004). Foxtail millet parameters were calibrated in agreement with observed data of northern Italy (Onofrii et al., 1990).

Sowing, harvest and cutting dates were chosen according to ordinary management of farmers. Typically maize, meadows and alfalfa were sown at the beginning of spring, while foxtail millet was planted in summer and winter wheat and Italian ryegrass in autumn. Four cuttings of alfalfa and meadows were simulated.

5.3.2.2. Crop management

In order to define the total amount of N fertilization in AC scenario, both in NVZs and nNVZs) the value of organic N from livestock (Figure 5.4) was derived for each district using the standard regional reference table (SIARL 2003-2007) that estimates the amount of manure-N as a function of animal type, age, fodder, housing system, etc (Regione Lombardia, 2008). In each district the organic N load was then split to crop rotations on the basis (i) of their percentage on the district area devoted to herbaceous crops, (ii) crop N requirement.

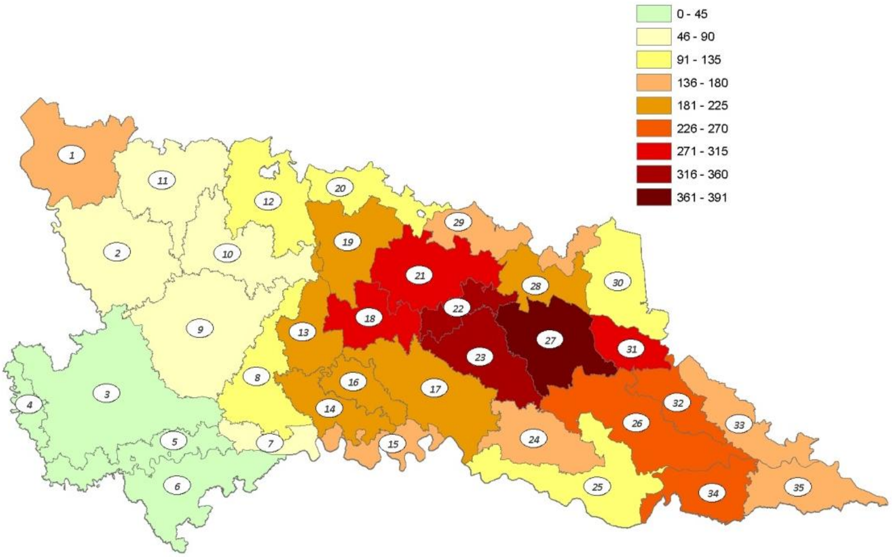


Figure 5.4. Organic N load (kg manure-N ha^{-1} UAA year^{-1}) for each district under AC (Regional Data Base SIARL, 2003-2007).

In AC scenario the calculated organic N fertilization was split in autumn (50%) and spring (50%) for maize, meadows, alfalfa. In the case of maize crops, once calculated the organic N input, the amount of mineral N fertilization was then calculated, in order to guarantee at least 350 kg N ha^{-1}year$^{-1,}$ as ordinary practice of farmers (Grignani and Zavattaro, 2000; Mantovi et al., 2006; Perego et al., 2011) . When organic load was elevated (250 to 450 kg N ha^{-1} year^{-1}), mineral N fertilization of 100 kg ha^{-1} year^{-1} was applied to maize. Winter wheat was fertilized by applying organic N only in 6 districts (14, 26, 27, 29, 33, 34) in the case of very high amount of N load per district, otherwise wheat was fertilized with 200 kg N ha^{-1}year^{-1} as mineral N. In ON170 and ON250 scenario thresholds of organic N fertilization were set on 170 and 250 kg N ha^{-1}year^{-1}, respectively. Particularly, in ON250 scenario manure N was applied only in spring or summer, avoiding any spreading on bare soil. Table 5.2 summarizes the N amount applied to crops under the three scenarios.

Table 5.2. Average N fertilization amount per crop under AC, ON170 and ON250 scenarios.

		organic		mineral	
Scenarios	**Crop**	**autumn**	**Spring**	**autumn**	**spring**
AC	**Maize**	**165**	**165**		**98**
	Wheat	**89**			**141**
	Meadows	**101**	**101**		**28**
	Alfalfa	**168**	**168**		
ON170	**maize**	**85**	**85**		**180**
	Wheat	**85**	**85**		**30**
	Meadows	**85**	**85**		
	Alfalfa	**85**	**85**		
ON250	**maize**		**250**		**100**
	Wheat				**100**
	meadows		**250**		
	alfalfa		**250**		
	maize 500 FAO		**250**		
	It. Ryegrass				
	Foxtail millet		**a**		**100**

a. Foxtail millet was manured in summer after wheat harvest at the end of June only in districts n. 16,19,26,27,28,33,34,35(250 kg N ha^{-1}) and no mineral N was applied.

With regard to irrigation, maize received from June to August by four irrigation treatments, whereas foxtail millet was irrigated by three, of 80 mm each. In districts 4, 5, 6, 7, 26, 32, 33, 34 and 35 irrigation events were 5 of 50 mm each for maize, being an area in which sprinkler irrigation is adopted. Foxtail millet was also irrigated by three irrigation events, with a water supply of 80 or 50 mm on the basis of what above described. Three districts were non irrigated (n. 1, 11 and 12) according to the ordinary agricultural practices of the area.

5.3.2. The ARMOSA model overview

In order to assess impact of derogation on water quality, nitrogen losses to water from the main agricultural systems under the specific conditions of Lombardia plain were estimated through a dynamic soil-crop model.

ARMOSA (Acutis et al., 2007) is a simulation model specifically developed on the basis of field trial data observed in ARMOSA project monitoring sites. ARMOSA implements several alternatives for each processes, using approaches already well known and largely validated in the scientific literature and used for practical application. In detail, reference evapotranspiration can be computed using Hargreaves, Priestley-Taylor or Penman-Monteith approach. Crop growth model development was based on SUCROS – WOFOST (a photosynthesis-based model from Wageningen school, used, among others application, at European scale for the Bulletin of yield prediction for wheat, maize and other important crops (Supit et al., 1994). Water dynamics can be simulated using the cascading approach, or the Richards' equation, solved as in the SWAP (Van Dam et al., 1997; Van Dam and Feddes, 2000) model. Such Richard equation solution has showed to be the best performing one with very detailed soil moisture data set (Bonfante et al., 2010). Nitrogen dynamics is simulated according to the SOILN approach (Johnsson et al., 1987, Eckersten et al., 1996), but with some improvements. In SOILN only three pools of organic and mineral nitrogen are simulated: humus, litter, manure, while in ARMOSA each type of organic matter has been differentiated with reference to mineralisation rates, respiration losses and C/N ratio, allowing for separate calculations for the different types of organic fertilisers or crop residuals incorporated into the soil. Depth of incorporation is also taken in account. As in SOILN, NH_4 and NO_3 pools are considered; NH_4 pool can be up taken by plants, oxidised to NO_3, fixed by the clay component of the soil, and immobilised in the organic matter; losses due to ammonia volatilisation are also simulated. NO_3 pool is subject to plant uptake, leaching and denitrification. Several options to use for medium-long time simulation are included: it is possible to define sowing and harvest DOY (day of the year), crop rotation, automatic irrigation, set of fertilization, LAI forcing, etc. Another improvement respect to SOILN model deals with plant nitrogen uptake; in SOILN this process is based just on the amount of transpiration mass flow of NH_4 and NO_3, whereas in ARMOSA crop uptake is also calculated on the basis of minimum, critical and maximum N dilution curve. Whereas plant nitrogen uptake in ARMOSA is characterised by the implementation, as in the CropSyst model, of an active mechanism based on the theory of nitrogen dilution. Soil temperature is also simulated, according to the Campbell (1985) approach. Objective of the model is to simulate crop grpwth, water and nitrogen dynamics in the soils representative of the Po valley agricultural areas, under different climatic conditions, crops and management practices, in order to have an instrument to extend the results of field trials to larger areas and to perform scenarios analysis. Results concerning model calibration and validation, which were carried out by using data observed from representative arable land in Lombardia plain, are detailed described by Acutis et al. (2011), *Chapter 4*.

5.3.3. Statistical analysis

A statistical analysis was carried out in order to test significance of scenario, crop and rotation in affecting N losses via leaching. The statistically significance was calculated by using SPSS 18.0 statistics package. A two-way ANOVA was executed ($\alpha=0.05$) for N leaching and crop yield, as dependent variables, alternatively. A pair-wais comparison was then calculated by using Dunn-Sidak's test (Sokal and Rohlf, 1981). In order to verify the effect of the different rotations in determining N leaching, a two-way ANOVA was executed where N leaching was the dependent variable, while rotation and scenario independent variables. A pair-wise comparison was then carried out with Dunn-Sidak's test.

In order to find a correlation between N leaching and independent factors involved in the studied continuum crop-soil, multiple step-wise linear regression was analyzed for each crop rotation. This type of regression analyzes combination of different factors, getting to a correlation explained only by significant factors. Within rotation, for each significant factor standard coefficient (beta) is calculated. Beta standard coefficients are the coefficients obtainable if all of the variables in the regression were standardized, including the dependent and all of the independent variables. By standardizing the variables before running the regression, variables have to be put on the same scale so that it is possible to compare the magnitude of the coefficients in order to verify which one has more of an effect.

5.4. Results

5.4.1. N leaching in scenario x crop

First, mean annual crop yield and N leaching were calculated for each scenario (Table 5.3) reports mean values of simulated crops yield and annual N leaching in each scenario, whose plots are reported in Figure 5.5 and Figure 5.6. As long as plot showed crop yield did not seem to differ particularly, whereas N leaching data appeared to be substantially lower passing from AC to ON250 and ON170 scenarios.

Table 5.3. Mean of annual crop yield and N leaching (kg ha^{-1} year^{-1}) for each simulated scenario. Yield is expressed in terms of dry above ground biomass, with exception of maize and wheat, being grain yield.

	crop yield	N Leaching						
crop	**AC**		**ON250**		**ON170**		**AC (nNVZs)**	
maize	**11849**	**61**	**11730**	**30**	**11751**	**39**	**11888**	**60**
wheat	**5840**	**16**	**6734**	**9**	**4621**	**24**	**6647**	**16**
meadow	**8419**	**12**	**9152**	**6**	**8383**	**4**	**7399**	**2**
alfalfa	**9887**	**27**	**9743**	**13**	**8269**	**8**	**5479**	**8**
maize 500			**16421**	**14**				
It. ryegrass			**3020**	**18**				
f. millet			**4124**	**16**				

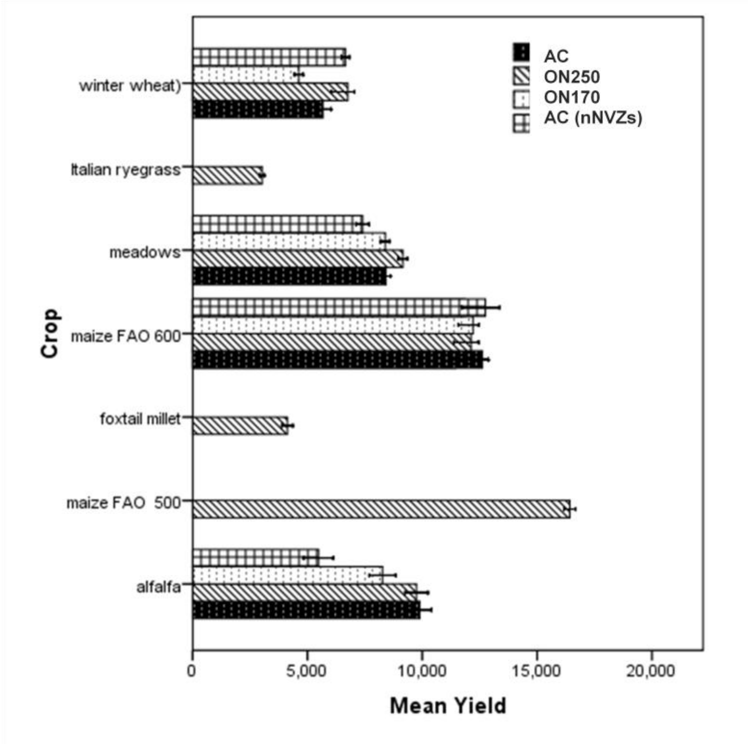


Figure 5.5. Mean of annual crop yield (kg ha^{-1} year^{-1}) for each simulated combination of scenario x rotation. Yield is expressed in terms of dry above ground biomass, with exception of maize and wheat, being grain yield.

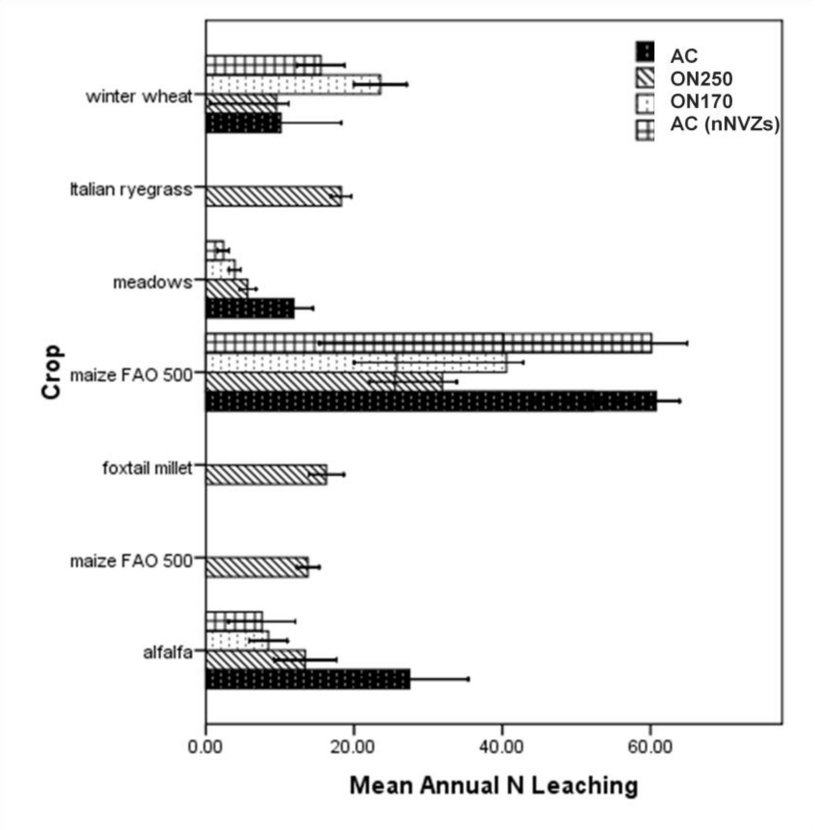


Figure 5.6. Mean of annual N leaching (kg ha^{-1} year^{-1}) for each simulated combination of scenario x rotation.

Regarding to crop yield, the interaction between the two independent factors resulted to be highly significant (p<0.001). In fact AC scenario was statistically different from ON250 and ON170, although ON250 and ON170 did not differ (p=0.112). The only crop which did not statistically differ in alternative scenario was maize crop, being particularly constant its yield. Alfalfa yield decreased significantly from AC and ON250 scenarios to ON170 and AC (nNVZs).

Wheat yield increased significantly from AC to ON250, while it decreased in ON250 scenario. In the case of meadow, AC (nNVZs) differed statistically (p<0.001) from the other scenarios, since crop yield decreased substantially.

As far as N leaching was concerned, scenarios resulted to be statistically different for $p<0.001$. In fact, N leaching resulted statistically different in each combination of scenario x crop, with no exception.

The outstanding result was the strongly decreasing of N leaching passing from AC to ON250 scenario. In the latter case half of losses resulted.

5.4.2. N leaching in scenario x rotation

Testing the effect of interaction between scenario and rotation on N leaching, a Dunn-Sidak's test was executed. Results of such pair-wise comparison allowed for a subsequent definition of homogeneous subset. In the case of leaching means resulted statistically analogous, for each scenarios a score was given to rotations by assigning a letter, where a was the best value being associated to lowest value of leaching (Table 5.4). In such way it was possible to identify which was the most sustainable rotation in terms of N leaching. B (permanent meadows) and G (alfalfa-maize-wheat) rotations resulted to be the best rotations in every scenario, while A rotation (monoculture of maize) the one associated to the highest leaching losses. D, F, H and L rotations had the second best score in every scenario. Figure 5.7 shows N leaching means simulated in the different combinations of scenario x rotations.

Table 5.4. Mean of annual crop yield and N leaching (kg ha^{-1} year^{-1}) for each simulated scenario.

	mean annual N leaching							
Scenarios rotations:	**A**	**B**	**D**	**E**	**F**	**G**	**H**	**L**
AC	**74c**	**11a**	**20a**		**40b**	**11a**	**37b**	
ON250	**32c**	**5a**	**16b**		**24bc**	**4a**	**19bc**	**16b**
ON170	**43c**	**4a**	**29b**		**20b**	**6a**	**14ab**	
AC (nNVZs)	**74c**	**2a**	**32b**	**2a**			**22ab**	

Numbers followed by different letter within a row are significantly different ($P\leq0.05$) according to Dunn-Sidak's test.

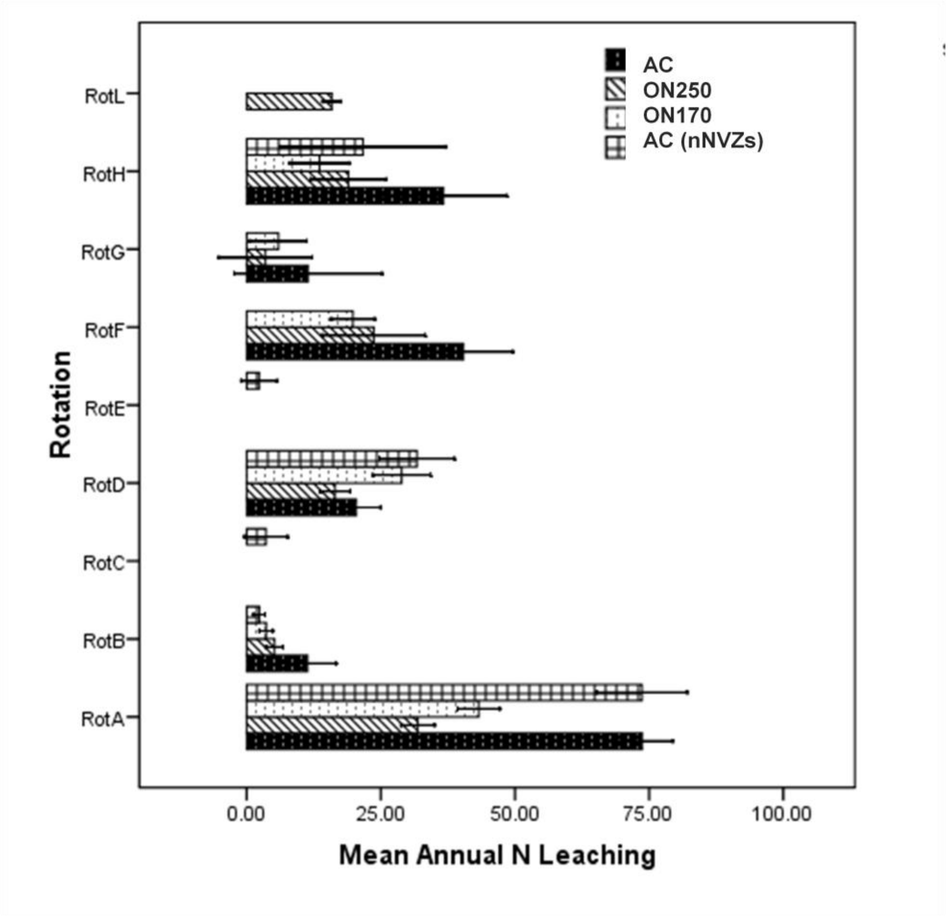


Figure 5.7. Mean of annual N leaching (kg ha^{-1} year^{-1}) for each combination of scenario x rotation.

Multiple linear regressions were executed within any rotation. The independent factors which were taken into account in this linear regression analysis were (i) organic N and (ii) mineral N fertilization, (iii) soil mineralization rate, (iv) rainfall + irrigation, (v) drainage water, (vi) soil sand % and (vii) clay % , (viii) soil organic carbon, (ix) bulk density , (x) crop yield, (xi) N uptake, and (xii) crop evapotranspiration (ET), (Table 5.5).

Table 5.5. Standard coefficients of a multiple step-wise linear regression of N leaching vs. independent factors.

	A	B	D	F	G	H	L
R^2	0.818	0.601	0.626	0.845	0.670	0.879	0.652
sig.	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Beta Standardized Coefficients							
organic N fertilization	0.41	0.652	-	-	-	0.942	0.186
mineral N fertilization	0.707	0.678	0.6	0.225	-	0.31	-
mineralization rate	0.891	0.506	1.165	0.825	-	-	-
rainfall + irrigation	-	-	-	0.875	-	2.011	-0.964
drainage	0.246	-	0.23	-0.436	0.818	-1.079	1.461
sand %	0.191	-	0.473	1.536	-	1.057	-
clay %	-0.167	-0.489	-0.572	-1.516	-	-	-
soil organic carbon %	-	-	-	-	-	-	0.364
bulk density	-	-	-	-	-	-0.578	-
Yield	-0.097	-0.335	-	-	-	-0.513	-
crop N uptake	-0.37	-0.241	-0.625	-	-	0.195	-0.348
crop ET	-	-	-0.228	-	-	-0.533	-

C and E rotations occurred only once so that analysis was not executed

Within each rotation studied factors had different statistically significance. Moreover, beta standard coefficients gave a measure of the weight of each factor. On average, drainage factor appeared to be mostly relevant within any rotation with exception of B rotation where drainage resulted fairly constant over years, districts and scenarios. Organic N fertilization did not score the highest beta magnitude in any rotation so that it was never prevalent factor among the others in affecting N leaching. Within A and D rotations mineralization rate was the most relevant, whereas in B mineral N fertilization, in F sand and clay content, in G and L drainage and in H the amount of H_2O input. In particular, in G rotation only drainage factor resulted to affect N leaching. That was probably due to constant trend of the other factors.5.4.3. N leaching in studied districts

After evaluating the simulated N leaching in scenario and rotations, the total amount of N leaching in each district was calculated for each scenario as weighted mean, taking into account the relative area of each rotation within any district. Figure 5.8 shows the total N leaching in AC, ON170 and ON250 scenarios, respectively. With regard to NVZs, a comparison between AC and ON170, ON250 showed a net decreasing of N leaching amount (Table 5.6).

Table 5.6. N leaching within districts in NVZs. % decreasing from AC to ON170 and ON250 scenarios are also reported

districts in NVZs	AC	ON170	decreasing (%)	ON250	decreasing (%)
2	24	24.0	1.1	17.8	26.8
10	22	30.3	0.2	13.8	36.9
11	12	15.6	2.7	7.9	31.6
12	19	31.6	2.0	9.7	50.0
13	55	31.9	42.3	23.2	57.9
16	37	20.9	44.3	13.8	63.1
17	29	17.1	40.6	14.3	50.4
18	28	8.3	70.1	6.9	75.3
19	36	20.3	43.7	13.7	62.0
21	70	39.9	42.6	21.1	69.6
22	99	44.4	55.2	27.3	72.4
23	50	21.8	56.8	10.2	79.9
24	11	6.4	43.4	4.6	58.8
25	13	11.1	11.4	5.6	55.4
26	26	13.5	47.9	8.8	66.1
27	81	37.9	53.0	37.3	53.8
28	40	19.3	51.2	9.5	75.9
31	84	49.2	41.1	33.3	60.1
32	29	9.9	65.5	8.1	71.7
33	23	19.2	17.9	10.7	54.2
34	25	8.6	65.8	9.5	62.5
35	10	6.8	30.1	4.0	58.3

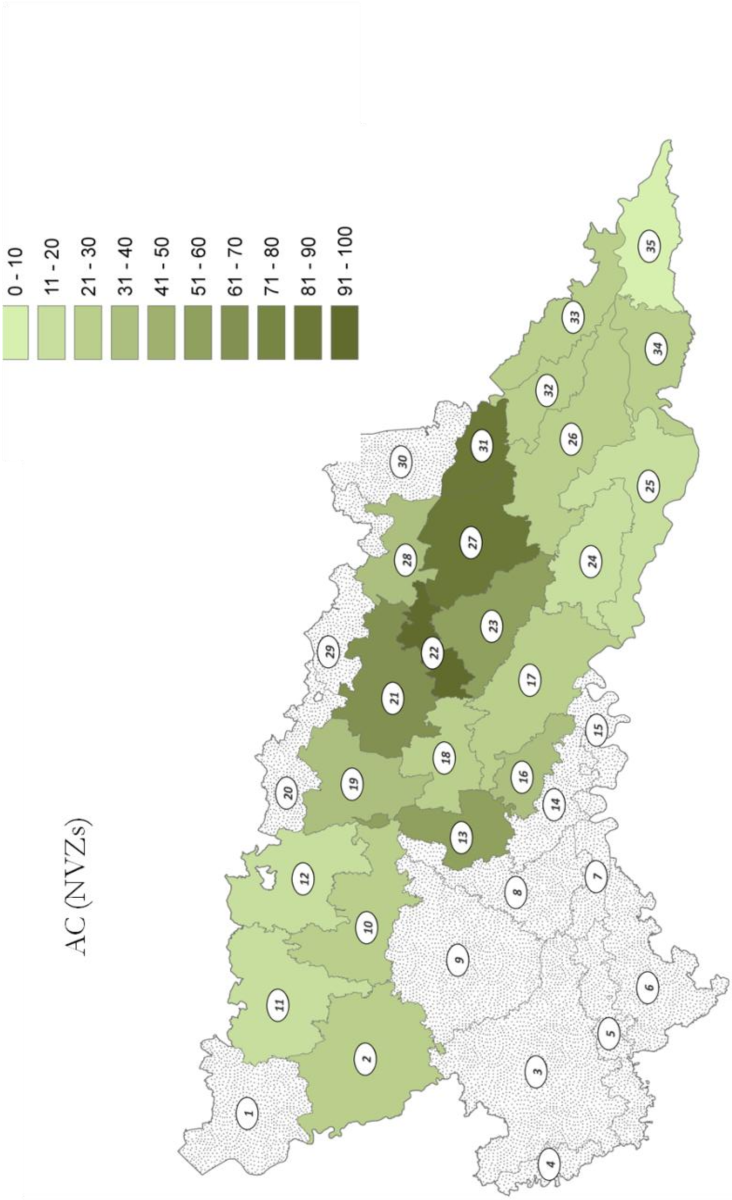
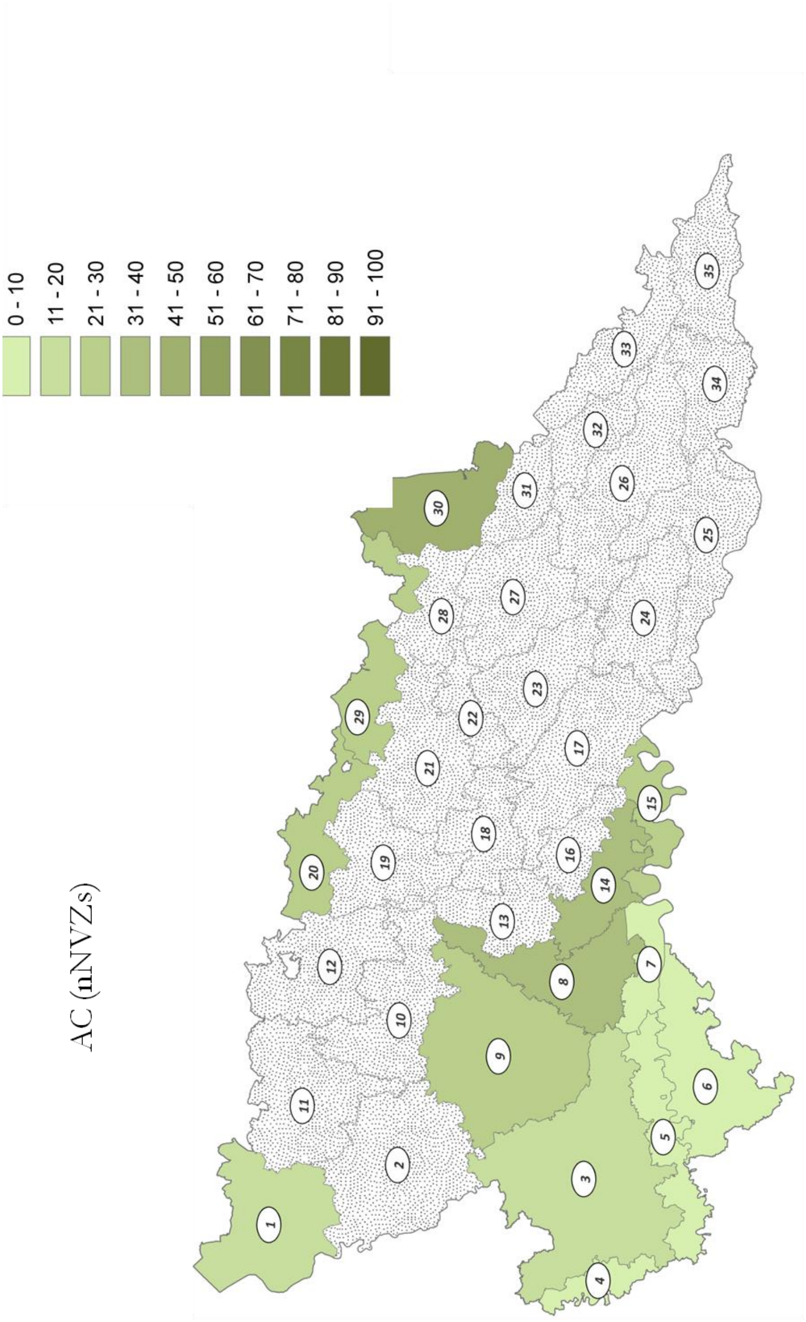


Figure 5.8a. Total amount of N leaching (kg N ha^{-1}year^{-1}) in AC (NVZs) scenario.

Figure 5.8b. Total amount of N leaching (kg N ha^{-1}year^{-1}) in AC (nNVZs) scenario.



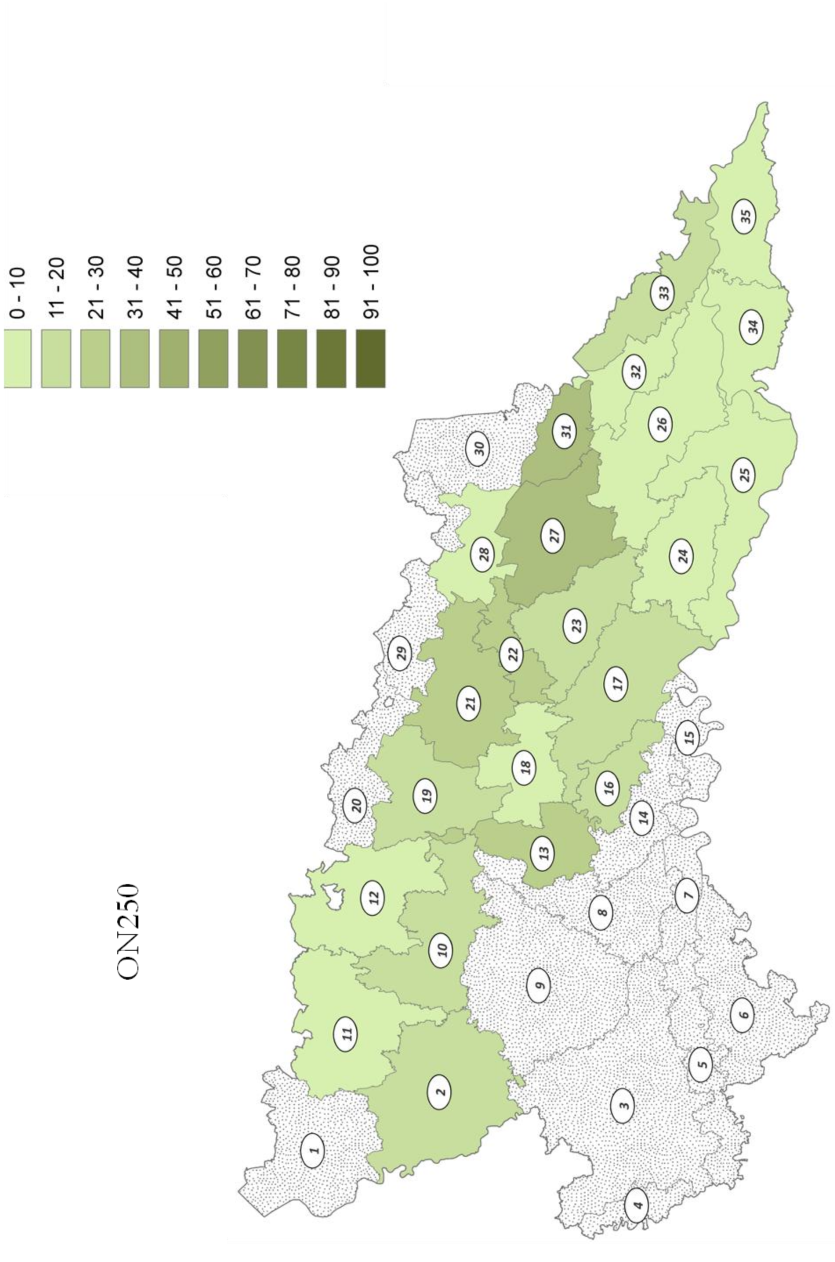


Figure 5.8c. Total amount of N leaching (kg N ha^{-1}year^{-1}) in ON250 scenario.

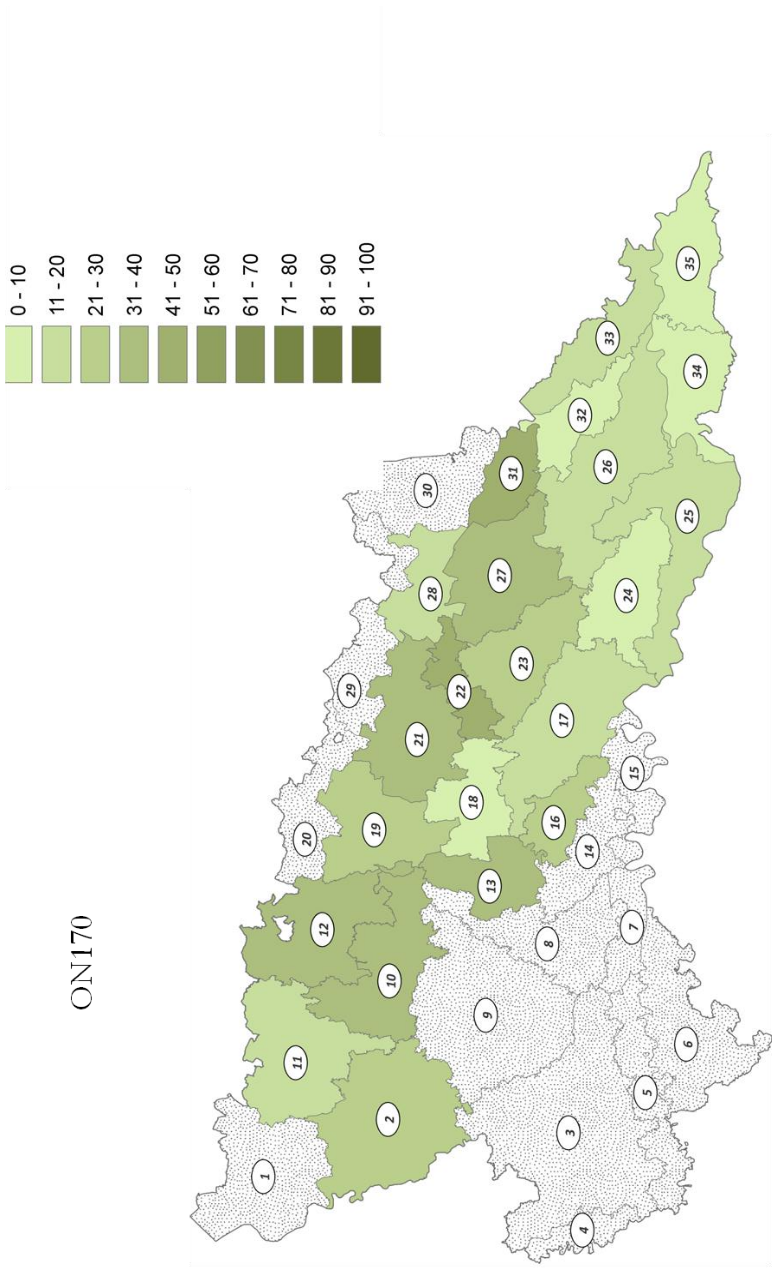


Figure 5.8d. Total amount of N leaching (kg N $ha^{-1}year^{-1}$) in ON170 scenario.

Mean N leaching amount were 37, 22 and 14 kg N ha^{-1} year^{-1} under AC, ON170 and ON250, respectively. ANOVA test confirmed the statistically significance of scenario factor in determining N leaching ($p<0.0001$). All executed post-hoc tests, such as Dunn-Sidak, Tukey, Duncan and Ryan-Einot-Gabriel-Welsch F, had confirmed that each scenario differed statistically to others (AC vs ON170 $p<0.0001$, AC vs ON250 $p<0.0001$, ON170 vs ON250 $p=0.035$). On average, N leaching decreased by 27% from AC to ON170, and by 59% from AC to ON250.

Evaluating N leaching within any district, the ON250 scenario resulted to be the best combination of cropping systems and agricultural management.

5.5. Discussion

ARMOSA model application allowed to analyze all the interactive factors determining N leaching from arable land, evaluating different cropping systems and management.

With regard to crop production the model simulated in agreement with existing studies carried out under similar conditions in Po plain. Considering grain maize production, Grignani et al. (2007) reported experimental results of trials in Piemonte (2003-2005) where grain yield was 12 Mg ha^{-1} with an average crop N up take of 200 to 300 kg N ha^{-1}. Such results are consistent with our simulated mean grain maize yield of 11.8 Mg ha^{-1} and a mean crop N up take of 279 kg N ha^{-1}. As far as winter wheat grain production and crop N up take are concerned, simulated values (5.9 Mg ha^{-1}, 160 kg ha^{-1}) are in fully agreement with regional average data (5.9 Mg ha^{-1}, ISTAT, 2010c) and experimental studies of Grignani et al. 2003, reporting a grain yield of 6 Mg ha^{-1} and an average N up take of 175 kg N ha^{-1}. The model underestimated silage maize and Italian ryegrass dry matter production if compared to field experiments (Onofrii et al., 1993; Grignani et al., 2003) although regional data confirmed an average dry matter production of Italian ryegrass of 3.2 Mg ha^{-1} (ISTAT, 2010d). Moreover, the simulated average of N up take of the double cropping systems was 279 kg N ha^{-1}, which does not differ from range of 248-293 reported by Grignani et al., 2003.

The simulated meadows production (8.5 Mg ha^{-1}) was slightly higher than regional data (ISTAT, 2010d), whereas simulated foxtail millet production (4.1 Mg ha^{-1}) and N up take (101 kg N ha-1) were consistent with results reported by Onofrii et al. 1990 from field trials in Po plain were ranges of production and N up take were 4 to 7 Mg ha^{-1} and 96 to 176 kg N ha^{-1}, respectively. Alfalfa simulated production (8.8 Mg ha^{-1}) was lower than results reported by Confalonieri and Bechini (2004) from field trials in Lodi (Lombardia plain), although higher than regional data (ISTAT, 2010d). In particular, alfalfa production significantly decreased from AC and ON250 to HY scenario because of less organic N fertilization (from 335 and 250 to 170 kg N ha^{-1}). In fact, the choice to yearly manure alfalfa, despite its negative effect on reduction of biological fixation, contributed positively to reduce N leaching. Results from Fumagalli (2009) and from Ceotto and Spallacci (2006) indicated that, increasing of organic N applied on alfalfa increased crop N uptake. Conversely, the choice to manure winter wheat in ON170 scenario involved significantly lower production. Such choice was forced to redistribute district organic N load among the existing rotations in order to be compliant with the current EU threshold of 170 kg organic-N ha^{-1} $year^{-1}$. In fact, under AC and ON250 scenarios winter wheat was generally not manured, preferring to apply manure to high N efficiency crop, as maize or alfalfa.

ARMOSA model calculated soil N balance. The N losses via leaching was in agreement with results reported in Po valley by Morari and Giupponi (1997) and Mantovi et al. (2006). Average volatilization of 11 kg N ha^{-1} $year^{-1}$ was consistent with data reported by Sommer and Hutchings (2001) under slurry spreading in Denmark. Simulated denitrification losses were 3.5 kg N ha^{-1} $year^{-}$

[1], being in agreement with data reported by Ventura et al. (2008). The overall N efficiency increased from 60 to 67% passing from AC to ON250 scenario. Although ON170 efficiency (70%) was higher than ON250's one, ON170 outline would not be possible to be pursued by farmers because of high livestock density. Particularly, in ON250 scenario N leaching represented 8% of N input, volatilization losses 4% and denitrification 1.6%. Therefore, 58% of N surplus was incorporated into soil organic matter through immobilization process. In the case of ON170, which was characterized by a crop N up take of 70% of N input, N leaching represented 9%, volatilization losses 4% and N denitrification 1.7%, so that 51% was incorporated to soil organic matter. ON250 management could contribute more than ON170 in enhancing soil organic matter. Grignani et al. (2007) confirmed that 45% of surplus N were incorporated into the soil organic matter value when farmyard manure was applied.

With regard to N leaching, B (permanent meadows) and G (alfalfa-maize-wheat) rotations resulted to be the best rotations in every scenario, while A rotation (monoculture of maize) the one associated to the highest leaching losses. D, F, H and L rotations, which includes maize as prevalent crop, resulted to be a good compromise between productivity and environmental sustainability.

The outstanding result of scenarios comparison was the significantly decrease of N leaching when the improved ON250 scenario is adopted maintaining crops yields and contributing to reduce N leaching losses to groundwater.

5.6. Conclusions

The ARMOSA simulation results indicated that ON250 appeared a good solution to face the current concern of N leaching in Lombardia plain.

Grain maize crops, as well as silage maize in a double-cropping systems with Italian ryegrass had an high N uptake. Moreover, the length of biological cycle of FAO 600 hybrids generally reached 150 days, so that crop N uptake corresponded to the period in which soil mineralization rate was particularly high. The increasing organic N supply and proportionally reduced mineral fertilization allowed for similar or even higher N use efficiency (N uptake/N input). The replacement of mineral N fertilizer with manure-N led to similar total N surface balance in maize-based forage systems, when manure N input was limited to 250 kg N ha^{-1} $year^{-1}$ threshold.

ARMOSA results show that winter wheat followed by summer herbage allowed for high N uptakes. Temporary grassland and alfalfa were able to assure reduced N losses via leaching.

Moreover, management proposed in ON250 scenario, could help in enhancing the soil organic matter and the efficiency of farmyard manure use.

Chapter 6

Conclusions

The plain area of Lombardia region is one of the intensive agricultural areas in Europe. The whole plain insists on the widest aquifer in Europe, that is potentially subjected to nitrogen leaching from agricultural sources. A major source of this NO_3–N is from the use of fertilizers for crop production. In fact, to ensure high crop yields, intensive use of production factors is common, namely nitrogen fertilisers and irrigation water. The large supply of N fertilizers involves elevated nitrogen surpluses even more when associated to frequent low efficiency irrigations, leading to an elevated risk of N leaching.

At six monitoring sites in Lombardia plain soil NO_3-N concentration and leaching was measured at real field scale. The analysis of such measured data indicated an high risk of leaching, especially in summer, with concentration exceeding the threshold of water drinkability of 50 mg L^{-1} NO_3, but also showed several possibility to be compliant with Nitrate Directive. It is possible to avoid any exceeding N surplus and then losses when the amount of N fertilizers is computed on the base of a nitrogen balance, together with a proper irrigation based on hydrological balance and crop water demand.

Dynamic models allow the simulation of N leaching from agriculture when crop growth and development, water and nitrogen balance are well described.

The ARMOSA simulation software, developed to predict N leaching risk from arable land in northern Italy, implements crop, water and nitrogen existing models which were previously tested and improved. The large data set measured at the six monitoring sites was used to calibrate and validate the model parameterization. Crop, water and N-related variables were accurately simulated, being in full agreement with observed data.

The ARMOSA simulation results indicated that crops with high N uptake and long biological cycle should be used in order to minimize N losses. Moreover similar or even higher N use efficiency resulted with increasing organic N supply and proportionally reduced mineral fertilization. According to such fertilization plan, when manure N input was limited to 250 kg N ha^{-1} $year^{-1}$ threshold, N leaching decreased by half compared to actual scenario in maize-based forage systems. The increasing of manure application can enhance the soil organic matter content and the efficiency of farmyard manure use.

Based on the results of this study, further research should be proposed with the main objective of define detailed management strategies to reduce N losses by (i) increasing the N use efficiency at farm and field scale and (ii) defining a water management able to minimize high rate of percolation. The methodology could include a modelling analysis together with field trials. In particular, the comparison between different N fertilization plans could lead to verify, under different pedoclimatic conditions, if the potential risk of N leaching is chiefly associated to chemical or organic fertilizers.

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Curriculum vitae

Alessia Perego was born March 20th, 1980 in Milano (Milano), Italy.

She graduated in July 2006 in Agricultural Sciences and Technologies (mark 110/110 *cum laude*) carrying out a modelling analysis, by applying STAMINA simulation crop model, of durum wheat growth under semi-arid climatic condition in hilly terrain.

From December 2006 to November 2007 she was Awarded of a fellowship in "Modelling management at territorial and field scale of irrigation water availability in semi-arid areas". She calibrated and validated the AQUATER simulation model from site-specific application to regional application.

In November 2007 she started her Ph.D. research at the Department of Plant Production. During this period she took part of ARMOSA project - "Monitoring network of soil water quality of arable land in Lombardia"- funded by Lombardia Region). Her work dealt with (i) collecting and storing data of monitoring site in Lombardia alluvial plain under intensive cropping systems, (ii) calibration, validation and continuous application of the model ARMOSA, evaluating different agricultural management at field scale to derive sustainable nitrogen managements at regional scale.