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DSSAT and **SALUS** modeling of nitrate leaching as influenced by manure and slurry application: evaluation of management options.

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…To the most important woman in my life,
my mother Carmen

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1. INTRODUCTION

1.1 Rationale

Nitrogen (N) is unique among the essential nutrients of higher plants in terms of its roles in biological systems and its complex cycling, it is the element most commonly limiting crop production and the one most demanding of management skills. Its addition to agricultural cropping systems is an essential aspect of modern crop management (Loomins and Connor, 1992; Robertson and Vitousek, 2009). The aims of agricultural N management are to provide enough nitrogen to plants to maximize growth and crop yields and to minimize pollution of other ecosystems.

In one direction, there is economic pressure to maximize land use efficiency and profitability, on the other hand there are environmental and ethical pressures to minimize pollution potential (Basso *et al.* 2009). Ideally, maximum profit and minimum pollution occur at similar N application rates. However, unpredictable weather patterns and varying product prices make difficult to achieve the optimal balance.

It is necessary to consider N fertilization in an environmental conscientious way; with improved understanding of such issues as correct application technology, source-sink relationships, and appropriate models, it is possible to achieve both efficient production and sound environmental production (Bacon, 1995, Robertson and Vitousek, 2009).

Agricultural users of organic wastes have, for decades, focused on maximizing the total economic value of wastes (primarily animal manures), by considering not only the value of the nutrients supplied but the costs associated with storage and handling. This has not always resulted in the best environmental management of wastes because reducing applications costs often was accomplished by adding too much manure to too little cropland. In most intensive agricultural systems, less than half of applied N is recovered in crops (Cassman *et al.,* 2002), much of the remainder is commonly lost to the environment. Humans have doubled the circulation of reactive N on earth, creating a N cascade in which added N flows through the environment, leading to degradation of air and water quality and coastal ecosystems in many areas (Vitousek *et al*., 1997; Galloway *et al*., 2003). Intense environmental pressures worldwide have forced a reexamination of organic wastes use by agriculture and the development of new, environmentally based waste management philosophies.

Environmental problems related to the use of N fertilizers and organic wastes focus primarily on the effects of nitrates (NO_3^-) and nitrous oxides (NO, N_2O), (Keeney,1982; Galloway *et al*.,2004; Crutzen *et al*.,2008) and includes: possible health hazards to humans and animals from either consumption of water high in NO_3^- or exposure to certain carcinogenic nitrosamines, eutrophication of surface waters by sediment organic N or soluble NO_3^- (Asadi, *et al*., 2002), formation of nitric acid (HNO_3) in the atmosphere from nitrous oxides emitted from soils, resulting in ecological damage from “acid rain”. Consumption of nitrates by humans and animals through drinking water has been associated with several health problems. The primary health hazard occurs when bacteria in the digestive system transform nitrate into nitrite. The nitrite oxidizes iron in the haemoglobin of red blood cells to form methemoglobin, which lacks the ability to carry sufficient oxygen to the individual body cells causing the infants to develop a blue coloration and respiratory problems known as methemoglobinemia or “blue baby syndrome” (Basso and Ritchie, 2005).

N compounds not only lead to eutrophication and acidification when deposited but also constitute a large fraction of the fine particles in the atmosphere that can affect human health and the radiation balance (Ferm *et al*., 2005). As a matter of fact NO_x emission contribute to the increase of tropospheric O_3 which is damaging crop production in some areas of the globe (Chameides *et al.,* 1992; Holland and Lamarque, 1997; Liang *et al.,* 1998; Powlson *et al.,* 2008). Nitrogen deposition onto formerly pristine areas also contribute to increased radioactive forcing through increased N_2O emissions (Mosier *et al*., 1998). In fact, photooxidation of ozone in the stratosphere by nitrous oxide (N_2O), increasing the ultraviolet radiation incident upon earth’s surface and the possibility of skin cancer and unpredictable ecosystem and climatic changes.

A large portion of this N deposition occurs on agricultural lands that needs to be accounted for in fertilizer recommendations, an aspect of the agricultural N cycle that has been ignored to date (Mosier, 2001). Several processes contribute to losses of N from agricultural systems, included here are runoff, denitrification, volatilization and leaching.

This research has been focused on the processes related to the leaching of nitrates into the soil and groundwater in the "*Nitrates Vulnerable Area from agricultural source*" of Arborea, Sardinia, Italy.

Nitrogen can be transported from organic waste-amended soils into ground-water by leaching. Losses of N by leaching occur mainly as NO_3^- because of the low capacity of most soils to retain anions.

In general, any downward movement of water through the soil profile will cause the leaching of NO_3^-, with the magnitude of the loss being proportional to the concentration of NO_3^- in the soil solution and the volume of leaching water. Leaching of nitrate-N is economically and environmentally undesirable (Katyal *et al.*, 1985; Poss and Saragoni, 1992; Theocharopoulos *et al.*, 1993; Basso and Ritchie, 2005).

Nitrate that leaches below the crop root zone represents the loss of a valuable plant nutrient and increases agricultural costs.

Much of the research conducted with animal manures and sewage sludges has been directed toward reducing NO_3^- leaching. Numerous studies have shown that NO_3^- leaching is a common and sometimes serious problem when organic wastes are used (Strebel *et al.*,1989; Ritter *et al.*, 1984 and

1987; Schepers *et al*. 1991; Weil *et al*., 1990; Basso and Ritchie, 2005) especially in humid regions. Situations most conductive to NO_3^- leaching and groundwater pollution include sandy, well-drained soils, with shallow water tables, in areas that receive high rainfall or irrigation and frequent use of fertilizers, manures, or other N sources, however, nitrate leaching concerns are not restricted to these situations. Any situation involving over-application of wastes and/or fertilizers, waste storage areas, or intensive irrigation has the potential to cause significant NO_3^- leaching regardless of soil and climate (Mielke *et al*. 1976; Adriano *et al*., 1975).

There are a wide range of measures available for reducing nitrate losses to groundwaters and surface waters. Measures include those associated with soil management, crop, fertilizer, manure and livestock management, land use change, and combinations of such measures.

The applicability and effectiveness of these measures varies with farming system, climate and soil type. However a major determinant of nitrate loss remains the livestock number and associated stocking density (and the associated inputs required to feed such livestock). On the base of all these issues, is of primary importance the necessity to improving the management and the efficiency in the use of all the N sources.

1.2 The nitrogen cycle: overview

Nitrogen (N_2) gas is by far the most abundant form of N, comprising 78% of the atmosphere, and is the main reservoir of the nitrogen cycle.

This form of N is unreactive and cannot be used by plants or animals. Nitrogen can be available in many different forms: as nitrate and ammonium (forms available to plants), as organic N, and in gaseous forms as ammonia and N oxides. Each of these forms of N has different chemical behaviour in the environment. Atmospheric nitrogen (N_2) can be fixed (i.e. converted into other N compounds) by bacteria, especially those associated with the root nodules of legumes.

In aquatic environments, blue-green algae have the ability to fix dissolved N, that is also fixed industrially in the manufacturing of fertilizers.

N is a component of all amino acids, which are the building blocks of proteins, and proteins are found in all organic material. Organic N is found in both living and decomposing organic matter. Soils contain large amounts of organic N resulting from the breakdown of plants, dead animals (insects, micro-organisms) and manures. Organic forms of N can be lost to water, both direct from land, and via sewage.

Soil microbes gradually convert organic N compounds into inorganic forms that plants can use. In fact, during the N cycle, N is converted from organic forms to inorganic forms as ammonia gas (NH_3) and the form it takes in water, the ammonium ion (NH_4^+), that are released during the decomposition of organic matter, also called mineralization.

Like nitrate, ammonium is used by plants as a source of N, and is commonly supplied to the crops as added directly in fertilizers.

Ammonia may be lost to the atmosphere from livestock manures and other sources by volatilization, and when re-deposited on semi-natural land causes acidification of soils and waters.

The process of mineralization provides a large proportion of crop N requirement even within intensive agricultural systems. Fresh residues may be mineralized relatively quickly, but only a small proportion of the soil N pool is mineralized in one year. Mineralization of organic N involves two reactions, aminization and ammonification, which occur through the activity of heterotrophic microorganisms that require organic carbon compounds for their source of energy. Recent studies demonstrate that the rate-limiting step in mineralization is the depolymerization of organic N, which is the breakdown of complex, insoluble N containing organic compounds by extracellular enzymes produced by microorganisms, leading to the release of soluble and biologically available organic compounds including amino acids (Schimel and Bennet, 2004; Robertson and Vitousek, 2009). Amino acids can be taken up by plants and microorganism (Nasholm *et al*., 1998), but in the relatively high conditions typical of most agro-ecosystems, most amino acid N is further transformed to inorganic forms before it is utilized by plants (Schimel and Bennet, 2004).

Mineralization increase with a rise in temperature and is enhanced by adequate, although not excessive, soil moisture and a good supply of oxygen. Decomposition proceeds under waterlogged conditions, although at a slower rate, and is incomplete. Aerobic, and to a lesser extent anaerobic, respiration release NH_4^+. Soil moisture content regulates the proportions of aerobic and anaerobic microbial activity. Maximum aerobic activity and N mineralization occur between 50 and 70 % water-filled pore space. Soil temperature strongly influences N mineralization, the optimum soil temperature for microbial activity ranges between 25 and 35°C. Immobilization is the conversion of inorganic N (NH_4^+or NO_3^-) to organic nitrogen and is basically the reverse of nitrogen mineralization.

If decomposing organic matter contains low N relative to carbon, the microorganism will immobilize NH_4^+ or NO_3^- in the soil solution. The microbes need N in a C:N ratio of about 8:1; therefore, inorganic N in the soil is utilized by the rapidly growing population.

N immobilization during crop residue decomposition can reduce NH_4^+ or NO_3^- concentrations in the soil to very low levels. Soil microorganism compete very efficiently with plants for NH_4^+ or NO_3^- during immobilization, and plants can readily become N deficient.

In most cropping systems, sufficient fertilizer N is applied to compensate for immobilization and crop requirements. After decomposition of the low N residue, microbial activity subsides and the immobilized N, which occurs as proteins in the microbes, can be mineralized back to NH_4^+.

If added organic material contains high N relative to carbon, N immobilization will not proceed because the residue contains sufficient N to meet the microbial demand during decomposition. Inorganic N in solution will actually increase from mineralization of some of the organic N in the residue materials (Havlin *et al.*1999).

The balance between mineralization and immobilization is also affected by organism growth efficiency. For example, fungi have wider C:N ratios in their tissues then bacteria and, therefore, have a lower need for N and will thus mineralize N more readily. As a general rule of thumb, materials with a C:N ratio > 25:1 stimulate immobilization, while those with a C:N ratio < 25:1 stimulate mineralization. The exception to this rule is highly decomposed substances with a low C:N ratio, e.g., soil organic matter (humus or compost) in which labile carbon and N have been depleted and the remaining carbon is in complex forms inherently resistant to decomposition and therefore resistant to mineralization.

It is important to recognize that mineralization and immobilization are occurring at the same time within relatively small volumes of soil.

As a result of the simultaneous nature and small scale of these process, it is also important to make a distinction between gross and net mineralization and immobilization. Gross N mineralization is the total amount of soluble N produced by microorganisms, and gross N immobilization is the total amount of soluble nitrogen consumed. Net N mineralization is the balance between the two. When gross mineralization exceeds gross immobilization, inorganic N in the soil is increasing, i.e., there is net mineralization.

When gross immobilization exceeds gross mineralization, inorganic N in the soil decreasing, i.e., there is net immobilization (Paul, 2007).

Nitrate (NO_3^-) and nitrite (NO_2) ions are oxidized compounds of N and are highly soluble in water. Nitrate is the product of the biochemical oxidation of ammonium using nitrite as an intermediary (nitrification), or can be supplied directly (for example as ammonium nitrate fertilizer).

Nitrification is important because, as anion, NO_3^- is more easily transported to roots and groundwater in respect to the cation NH_4^+, as most agricultural soil have little anion exchange capacity. NO_3^- can replace oxygen as terminal electron acceptor in the course of microbial respiration by which NO_3^- is reduced to N_2 and to N containing trace gases.

Also importantly, in most annual crops, N is taken up mostly as NO_3^-, and without nitrification, not much nitrate would be available (Bloom, 1997). Because nitrification is a microbial process, soil environmental condition influence nitrification rate. Generally the environmental factors favoring the growth of most agricultural plants are those that also favor the activity of nitrifying bacteria. Factors affecting nitrification in soil are: supply of NH_4^+; population of nitrifying organism; soil pH (range from 4.5 to 10, although the optimum pH is 7.5 - 8.5); soil aeration (aerobic nitrifying bacteria will not produce NO_3^- in the absence of O_2); temperature (optimum soil temperature for nitrification is 25 to 35°C). Nitrate is commonly found in soil and water and, as mentioned before, is one of the main forms by which plants obtain their N. In fact, the nitrate form is most effective in promoting plant growth, but is also most readily lost from soil by leaching in drainage water.

The most important losses of N from ecosystems include denitrification to N_2, leaching to surface and groundwater, volatilization of NH_3 and fluxes of N_2O and NO_x to the atmosphere. Although not specific to the N cycle, erosion by wind and water removes N in various forms from agricultural ecosystems (Pimentel and Kounang, 1998; Robertson and Vitousek, 2009). Denitrification of nitrates and nitrites to N and nitrous oxide gas occurs in soils, especially when there is a good supply of nitrate, an high pH, a temperature range from 2 to 25°C and a poor supply of air, for example, under waterlogged conditions.

Nitrogen oxide is the generic name for N oxide (NO) and nitrogen dioxide (NO_2). These gases are produced by soil bacteria and through the combustion of fuels. These oxides are implicated in global warming, acid rain and N deposition, and in the formation of precursor pollutants including ozone (O_3). Nitrous oxide is a gas released from the soil during the decomposition of organic matter and N fertilizers. It is also produced in some industrial processes such as the production of nylon.

Ammonia is lost by volatilization from animal production systems, soils and plants. NH_3 is in pH-dependent equilibrium with NH_4^+ in soils and solutions; most losses by volatilization from soils happen after fertilization when both presence of large quantity of NH_4^+ and pH can be high.

Losses of NH_3 from plants directly to the atmosphere can also occur, especially during senescence (Schjoerring *et al.*, 1998). Leaching of NO_3^- is one of the largest losses to the environment in most cropping systems; while some dissolved organic N and NH_4^+ are lost to surface and groundwater, the mobility of nitrates ensures that is normally the dominant form of dissolved N in water moving through agricultural soil profiles (Robertson and Vitousek, 2009). The nitrate leaching process has been discussed in the previous paragraph, while in the next one will be presented a literature review on this topic. A schematic of all the processes related to the N cycle is represented in figure 1(Havlin *et al.*, 1999).

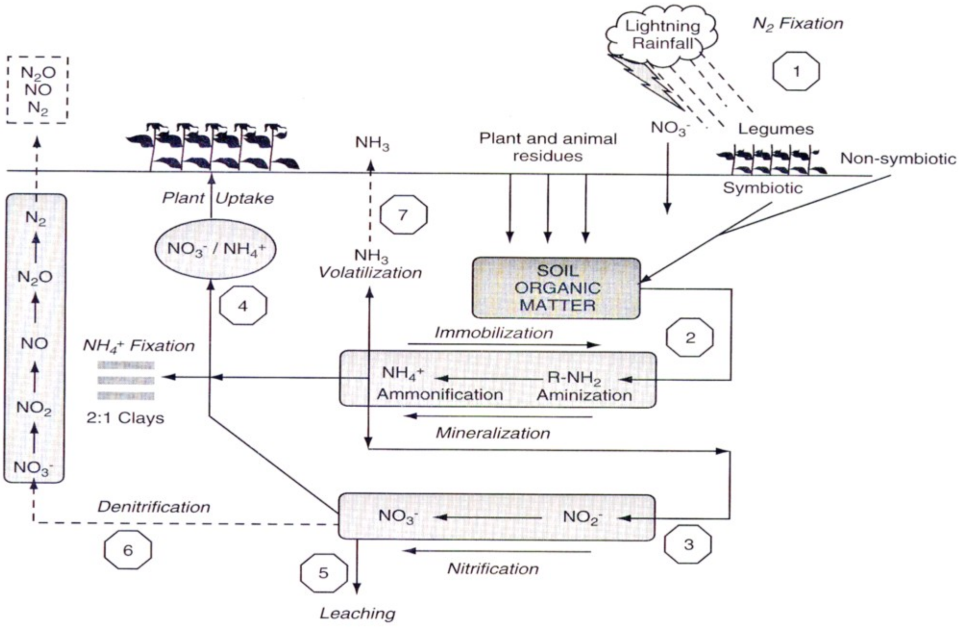


Figure 1. Schematic of the Nitrogen Cycle (Soil Fertility and Fertilizers; *An Introduction to Nutrient Management;* John L.Havlin, James D. Beaton, Samuel L. Tisdale, Werner L. Nelson; 86 (4); 6th Edition; Prentice Hall 1999).

1.3 Literature review on nitrate leaching

Precise estimation of nitrate leaching from agricultural systems is critical to environment impact studies. Accurate nitrate leaching can be assessed through various sampling methods. Researchers have measured nitrate N concentration in soil and drainage water from tile lines, well water and soil water samples (Basso and Ritchie, 2005). Even if nitrate concentrations as high as 120 mg L^{-1} in tile lines under maize production have been reported (Logan *et al.,* 1980) ranges from 10 to 80 mg L^{-1} are more common (Haigh and White, 1986; Steenvoorden *et al*.,1986; Martin 1992; Owens *et al*., 1999). Tile effluent correspond to only a portion of the water that moves through the soil, as a result the tile-flow method underestimates losses of nitrate from leaching (Smith *et al*., 1990; Owens *et al*., 2000).

Otherwise, lysimeters afford a means to quantify total water flow and N movement through soil. Bergstrom (1990) acknowledges that lysimetry offers a reasonable method to carry out investigations under field conditions that are subject to actual environmental influences.

In the past decades lysimeters have been used for various different studies, including evapotranspiration measurements (Ritchie and Burnett, 1968; Ritchie, 1972), nitrate leaching quantification under different crops (Reeder, 1986; Tyler and Thomas, 1977; Bergstrom, 1987; Owens, 1987; Prunty and Montgomery, 1991; van Es *et al.,* 2006) and management impacts on nitrate leaching (Shipitalo and Edwards, 1993; Martin *et al.,* 1994 and 2006; Baker and Timmons, 1994; Basso *et al*., 1995; Rasse *et al*., 2000; Basso and

Ritchie, 2005). Many of these studies have been focused on inappropriate land fertilizers application leading to excess N in the form of NO_3-N moving downward in the soil profile in excessive rainfall and/or irrigation-based leaching. Trindade et al. (1997) measured nitrate leaching from a double-cropping forage system including maize and a winter crop consisting of a mixture of cereals and Italian ryegrass, over a 2 year period in the Northwest region of Portugal, using ceramic cup samplers to extract soil solution under suction at 1 m depth. The experiment was performed on two different sites differing in the amounts of N applied as fertilizer and by regular cattle slurry applications. The annual nitrate leaching losses measured ranged from 154 to 338 Kg N ha^{-1}. These amounts lead to annual mean concentrations between 22 and 41 mg NO_3^- -N L^{-1} in the drained water. Jemison and Fox (1994) compared nitrate-N leaching from liquid dairy manure and chemical fertilizer treated maize, measured with zero-tension pan lysimeters, and found that both sources resulted in NO_3-N concentrations in excess of USEPA (*United States Environmental Protection Agency*) drinking water standard (10 mg L^{-1}).

Basso and Ritchie (2005) compared the effects of manure, compost and inorganic treatment on nitrate leaching using large undisturbed monolith lysimeters over six years of maize-alfalfa rotation in Michigan.

The results observed in this study showed that the manure treatments always reached higher nitrate leaching compared to the other treatments. The total amount of nitrate leached in the manure treatment as sum of the two rotations considered in the study was 681 Kg NO_3-N ha^{-1} followed by the compost with 390 Kg NO_3-N ha^{-1} and the inorganic treatment with 348 Kg NO_3-N ha^{-1}. The highest rates of NO_3–N losses were also observed in the manure treatment with a mean value for the six-year rotation of 0.14 kg NO_3–N mm^{-1}. Yields did no differ among treatments or between treatments and unfertilized controls.

In general, these studies found the highest NO_3-N levels under maize, intermediate levels under less fertilized annual crops (e.g., soybean and wheat), and lowest levels under perennial crops (e.g., alfalfa and grasses). Therefore, the process of nitrate leaching under different crops involves a complex interaction among soil hydrology, crop water and nutrient uptake and management practices. Also, the processes governing leaching are strongly affected by soil type.

van Es *et al*. (2006) found that NO_3-N leaching concerns are more acute for the sandy loam soil than the clay loam soil due to higher hydraulic conductivity and lower retentivity; similar conclusion by Sogbedji *et al.* (2000), Geleta *et al.* (1994), and Korsaeth *et al.* (2003).

Higher concentrations may also in part be the result of greater NO_3-N levels due to a higher manure mineralization potential on well-drained soil (Magdoff, 1978), and lower denitrification potential (Sogbedji *et al*., 2001 (1); 2001 (2)). Nitrate leaching has also modeled in various systems and ways, in fact, there are many models able to simulate the agricultural management effects on N loss.

Worthy of mention are CREAMS (*Chemicals Runoff and Erosion from Agricultural Management Systems;* Knisel, 1980); EPIC (*Erosion-Productivity Impacts Calculator*; Williams *et al*., 1984); GLEAMS (*Groundwater Loading Effects of Agricultural Management Systems*; Leonard *et al*., 1987); DAISY (*Soil Plant Atmosphere System Model*, Hansen *et al*., 1990); DSSAT (*Decision Support System for Agrotechnology Transfer*, Tsuji *et al*., 1994); and SALUS (*System Approach to Land Use Sustainability;* Basso *et al*., 2006).

In this research the DSSAT and SALUS models have been tested to a field scale experiment in the Nitrates Vulnerable Area of Arborea.

These two models have been widely used by numerous researchers worldwide for many different purposes, including predict nitrate leaching. Example of DSSAT model application on this topic are: *Testing simulation model for the assessment of crop production and nitrate leaching in Hungary* (Kovács et al., 1995), *Estimating nitrates and water in two soil* (Beckie *et al.,* 1995), *Nitrate leaching potential in Minnesota soil and predictions of nitrogen mineralized from cover crops residues* (Quemada and Cabrera, 1995), *Evaluation of the CERES-Maize water and nitrogen balances under tile-drained conditions* (Garrison *et al*., 1999).

Zeniali *et al*., 2009 studied the effects of different scenarios of N fertilizers application and soil profile on the nitrate leaching under rainfed and irrigated winter wheat in Gorgan, of Iran, using DSSAT cropping system model.

Basso *et al*. (2009) presented a procedure that allowed to identify the optimal N fertilizers rates to be applied spatially on previously identified management zones based on agronomic, economic and environmental sustainability of N management through the use of the DSSAT-CSM.

Basso et al. (2010) also, presented a study based on the use of the SALUS crop simulation model in which were evaluated the efficiency of crop N uptake in a long-term wheat crop in a Mediterranean environment of southern Italy, identified optimal N rate for reasonable economic returns and minimum nitrate leaching.

1.4 Legislation of the nitrates vulnerable zones from agricultural sources.

The Nitrate Directive 91/676 (EEC, 1991) agreed by the EC Environment Council in 1991, is an environmental measure to protect all types of surface and groundwater bodies against nitrate pollution from agricultural sources.

The main objective of the EU Nitrate Directive is to reduce water pollution caused by nitrate from agricultural sources and to prevent further pollution (Børsting *et al*., 2003).

Particular emphasis has been given to drinking waters, but this Directive encompasses all waters including assessing the likelihood of eutrophication.

There are four main requirements:

- Identify ‘polluted waters’ and the associated contributing area (vulnerable zone) in Member States;
- Identify areas where the nitrate concentration of surface or groundwater already exceed 50 mg L^{-1} or is likely to exceed this figure;
- Establish a mandatory “action programs” in the designated vulnerable zones, including Codes of Good Agricultural Practice;
- Monitoring, reporting and reviewing designations and effectiveness of Action Program on a regular basis.

The EC Directive on Nitrate provides scope for integrated controls on land use through designation of Nitrates Vulnerable Zones (NVZs) where farming practices are restricted and the timing and application of manures and N fertilizers are controlled. Where surface waters or groundwater exceed or are at risk of exceeding 50 mg L^{-1}, then NVZs are designated.

In Italy, the Legislative Decree 152/06 (ex. 152/1999) imposed the individuation of the Nitrates Vulnerable Zones to all regions, the monitoring of the underground water and the definition of an “Action Program” to give more information to the farmers and to reduce pollution.

The Independent Region of Sardinia identified, in 2005, an area of 55 Km^2 in the “Municipality of Arborea” (Latitude 39° 46' 26" N; Longitude 08° 34' 53" E; Altitude 7 m.a.s.l.) on the west-coast of Sardinia, Italy, as a NVZ

(Executive Resolution of the Giunta Regionale n. 1/12 del 18.01.2005 “Directive 91/676/EEC”), because of:

- The presence of 163 farms for animal husbandry productions;
- The presence of more than 50 mg L^{-1} of nitrates in superficial and groundwater;
- The presence of about 35,600 dairy cattle raised in intensive systems;
- The use of large quantities of organic fertilizers;
- The presence of underground water at the depth of 60 – 140 cm.

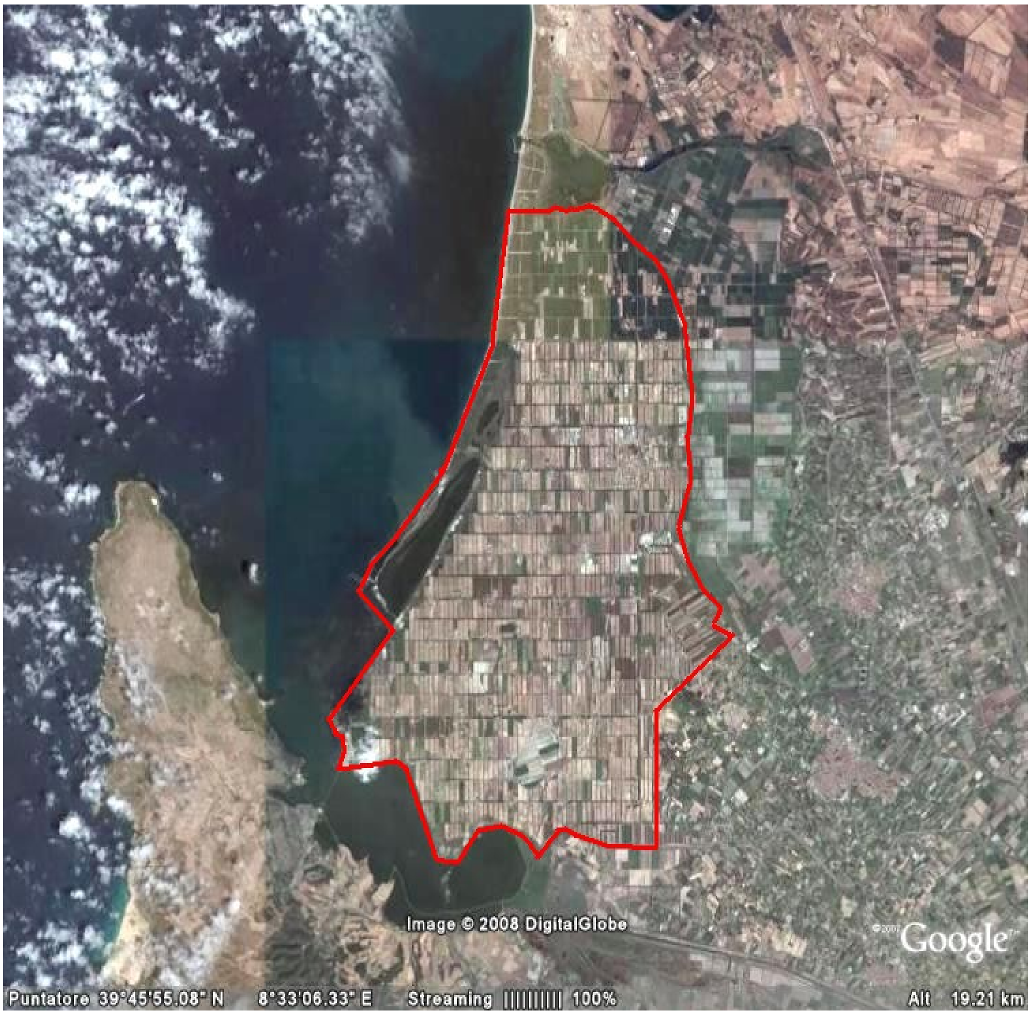
In addition, in this area, the soil has an high concentration of sand (more than 90%). On sandy soils, the soil is permeable and excess water continues moving downwards beyond the root zone on its journey to groundwater and some or all of the nitrate which was initially present in the soil will have been displaced to below the root zone and will not be recoverable by crops.

In the NVZ of Arborea the farmers, in the last seventy years, in efforts to improve the quality and quantity of harvest, have used organic and mineral fertilizers rich of N that increase the quantity of nitrates absorbed by the ground. This causes leaching of nitrates that can reach extremely high levels in combination with inadequate agronomical practices.

Obviously, the impact of agriculture on regional water quality will become more evident when agriculture is the dominant form of land use.

What may initially look like a negligible diffuse loss from the field of an individual farm, may eventually have serious consequences where the effects of numerous small diffuse sources accumulate (Burt and Haycock, 1991). According to the EU Nitrate Directive (91/676/EEC), in Italy, was introduced the Ministerial Decree 04/17/2006 (published in the Official Journal n° 109, in date May 25th 2006). This Decree includes the P.U.A. ("Piano di Utilizzazione Agronomica dei reflui zootecnici", standing for "Agronomic Fertilizing Plan with manures") which defines the fertilization practices adopted in the NVZs respecting the limits in the use of organic fertilizers, such as manure and slurry. The PUAs are compiled by professional advisors and are evaluated, eventually approved, by agronomists of the public administration. After approval, the farmers are authorized to apply manure on their farm fields (Provolo, 2005).

In conformity with the P.U.A. a maximum of 340 kg ha^{-1} of N from animal manures can be spread per hectare per year and only 170 kg ha^{-1} $year^{-1}$ of N in vulnerable areas. The manure allowed per hectare is calculated as N excreted by animals minus N volatilized in the atmosphere during housing and storage (Webb, 2001). The last term for the presentation of the P.U.A in the NVZ of Arborea has been set for the November 13th 2007, with the obligation of resubmit it every year within the date of September 30th.



Picture 1. Aero-view of the Nitrates Vulnerable Zone of Arborea.

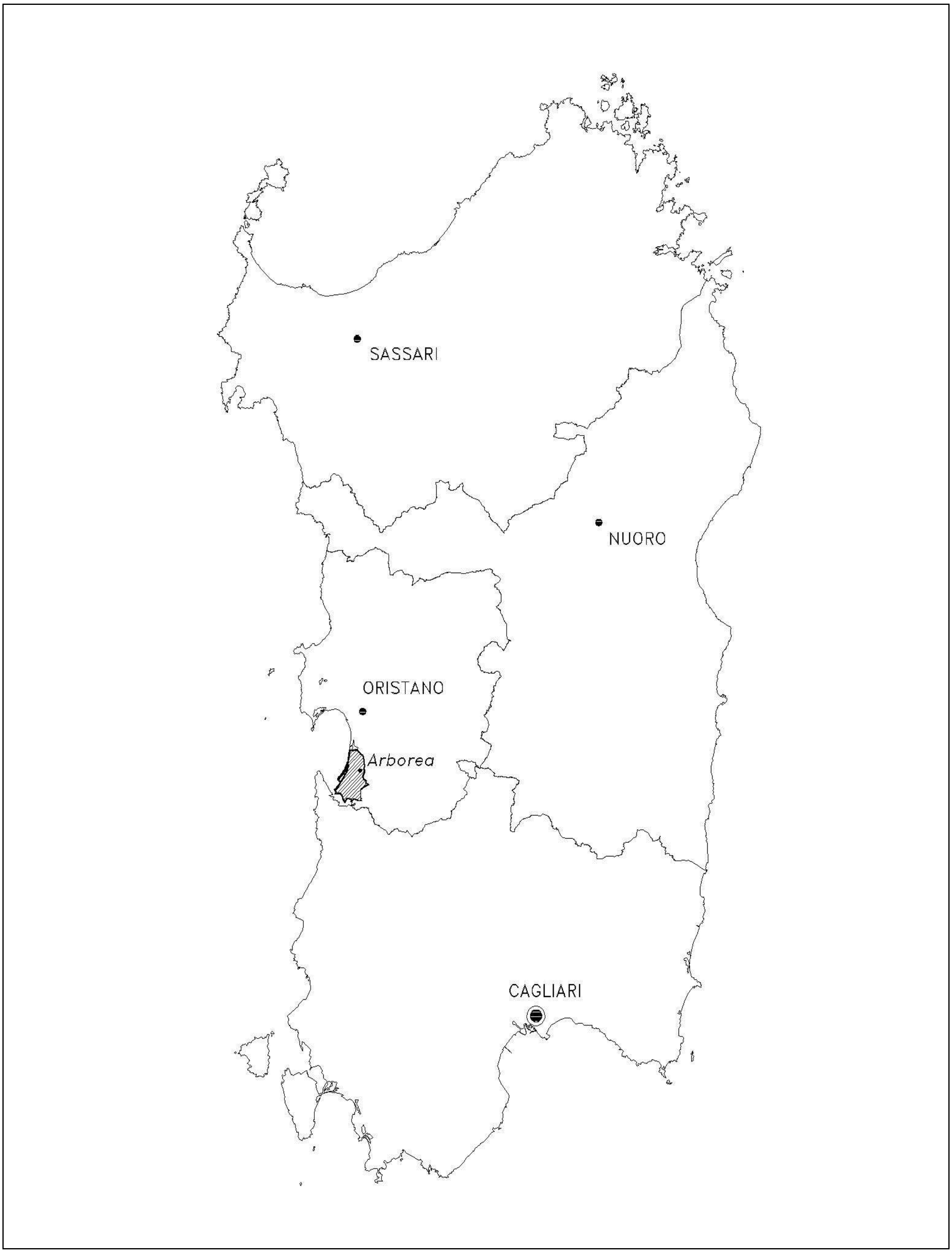


Figure 2. Regional map of Sardinia: the dashed area represents the Nitrates Vulnerable Area of Arborea.

Figure 3. Detail of the Nitrates Vulnerable Area of Arborea.

2. OBJECTIVES

At the onset of the experimental work the hypothesis was that the long term overuse of mineral and organic N fertilizers, especially in irrigated sandy soil areas increases the quantity of nitrate in the soil and nitrate leaching. The use of simulation models can help to assess and understand the dynamics of nitrates in the soil and the process of nitrate leaching related to different types of agronomical management.

The main objectives of this research were: i) to quantify inorganic N concentration in soil layers affected by different organic fertilization in the nitrates vulnerable zone of Arborea; ii) to calibrate and validate the DSSAT (*Decision Support System for Agrotechnology Transfer*, version 4.5) and the SALUS (*System Approach to Land Use Sustainability*) cropping system models to simulate the effects of manure and slurry application on soil N and nitrate leaching in the maize – triticale – maize rotation for the study period (2007 – 2008) and for a long term weather record (1959 – 2008);

iii) use the models to determine the best management strategies for irrigations and N fertilization through a selection of scenarios, to reduce the risk of nitrate contamination from agricultural sources maintaining a sustainable production.

3. MATERIALS AND METHODS

3.1 Area of study and farm description

This study is part of a research founded to the *Department of Agronomic Sciences and Agriculture Genetics* and the *Department of Animal Science* of the University of Sassari. The research was carried out in the years 2007 – 2008, on a private farm, near to the city of Arborea.

This area has about 35,600 dairy cattle raised in intensive systems. Lactating cows account for 57 % of the total cattle and produce about 80% of the total volume of dairy husbandry wastes in Arborea. Waste of cubicle housing farms stored in tanks represents 78% of the volume produced solely by the lactating cows, and 58% of the total amount of the waste produced by all dairy animal categories. The remaining part of the waste is accumulated in the manure of the barns in which a bedded pack system is used (ERSAT, 2005).

Due to the prevalence of the cubicle housing system in Arborea, the farm in which the measurements were carried out was characterized by this type of housing. The selected farm had an extension of about 75 ha, and is located at about two kilometers from the centre city of Arborea.

The farm had fifty-hundred Holstein Friesian cows and 40% of the herd was composed of lactating cows. The farm had facilities to store the manure and slurry produced by the cattle, and to process and separate the solid part of the slurry from the liquid part.

3.1.1 Experimental field

The experimental field had a size of 4 hectares in which maize (*Zea mays L.*) and triticale (*x triticosecale WittMack*) were cultivated and harvested for silage. This rotation represent one of the most typical agricultural system of the NVZ of Arborea.

The experimental field was divided into two equals parts of 2 hectares and in both parts, during the crops growth, were distributed mineral fertilizers while, before the sowing of maize crops, in the east part of the field was distributed manure whereas in the west side was slurry.

However, about one months before the sowing of the triticale crop was distributed slurry on the entire surface of the field (4 ha).

Picture 2. Experimental field

3.1.2 Meteorological data

The area of study, situated in the western Mediterranean sea, is characterized by a typical Mediterranean climate, with long, hot, dry summers and short, mild, rainy winters with a long-term average annual rainfall of 567 mm, mainly occurring between October and April. The prevalent wind is north-westerly and blows over the island in all seasons. Several natural permanent pools or lagoons (Mistras, Marceddi, S. Giovanni, S'ena e Rubbia, Corru de S'Ittiri and S. Giusta) and some seasonal ones which dry up completely during the summer are situated in the plain along the coast.

The meteorological data of the region during the experimental period were taken from the meteorological station at the experimental farm "Santa Lucia" (Zeddiani, OR; Latitude 39°56'03.11" N, Longitude 8°41'13.41" E, 15 m altitude) of the *Department of Agronomic Sciences and Agriculture Genetics* of the University of Sassari, at about 20 Km from Arborea.

The meteorological data relative to fifty years (from 1959 to 2008), were taken from the same meteorological station, to made a "long run seasonal and rotational experiment" with the DSSAT and SALUS models.

The meteorological data used were: daily maximum and minimum temperature, rainfall and solar radiation. The solar radiation was calculated using the equation proposed by Campbell and Donatelli (1998).

3.1.3 Weather patterns

The climatic parameters (rainfall, maximum and minimum temperatures) measured in the meteorological station of "Santa Lucia" in the years 2007 and 2008 are reported in the figures 4 and 5.

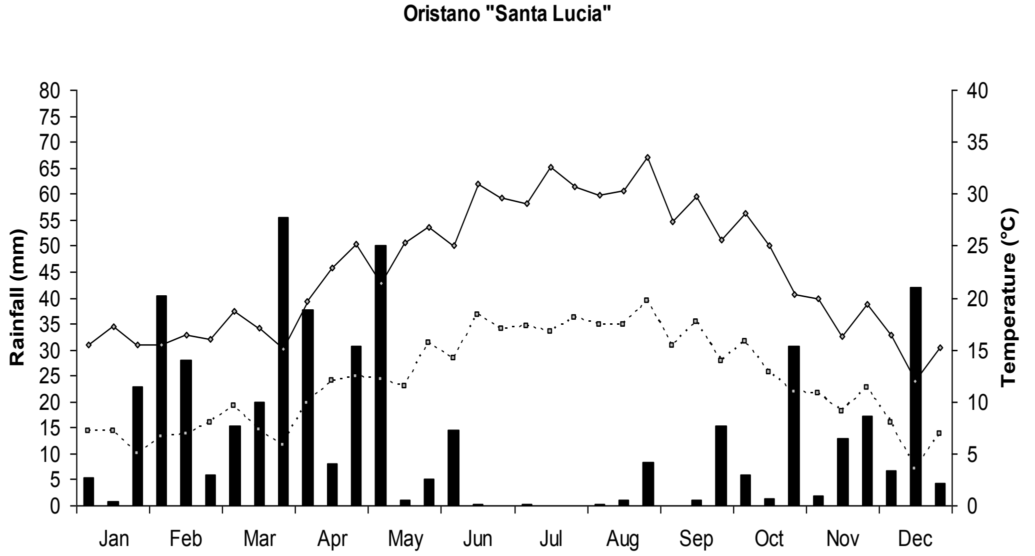


Figure 4. Rainfall (bars), maximum (solid line) and minimum (dashed line) temperatures from 1 January to 31 December 2007. Rainfall values are sums, and temperature values means, over 10-day periods.

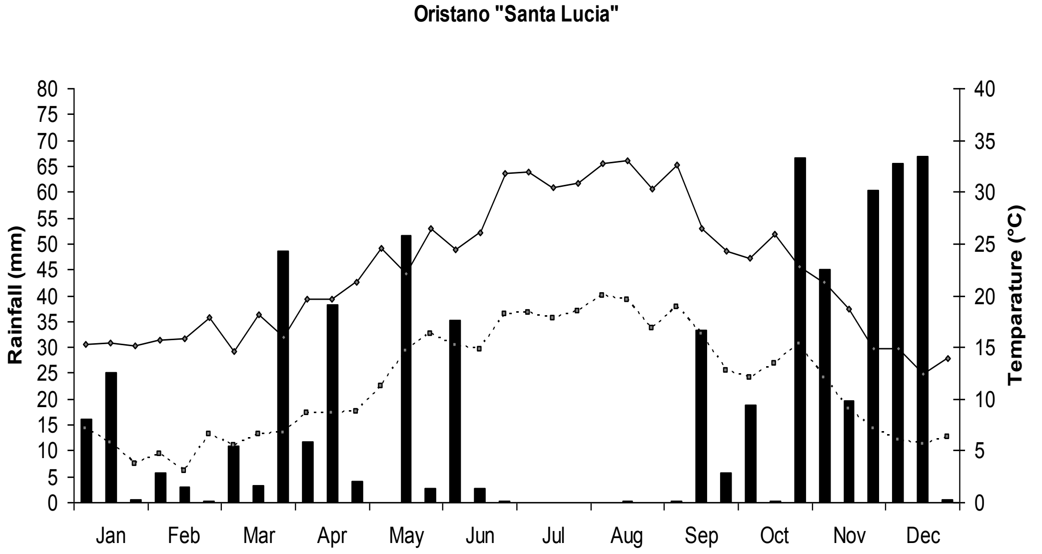


Figure 5. Rainfall (bars), maximum (solid line) and minimum (dashed line) temperatures from 1 January to 31 December 2008. Rainfall values are sums, and temperature values means, over 10-day periods.

The amount and distribution of rainfall varied widely between the two years. A total of 491.1 mm of rainfall occurred in 2007, with a maximum of 90.6 mm in March and a minimum of 0.4 mm in July; while 643.6 mm fell in 2008, with a maximum of 133.0 mm in December and a minimum of 0.0 mm in July. In both years temperatures were close to the long term averages. The absolute maximum temperatures were 39.1°C and 39.9°C in the month of August, in 2007 and 2008 respectively; whereas the absolute minimum temperatures were 0.4°C in January 2007 and -1.0°C in February 2008. The 50 years (from 1959 to 2008) climatic parameters (rainfall, maximum and minimum temperatures) are reported in figures 6 and 7. Figure 6 shows the monthly 50 years averages of climatic parameters and figure 7 shows the seasonal 50 years averages of climatic parameters related to the maize growing season (from May to September) measured in the meteorological station of “Santa Lucia”.

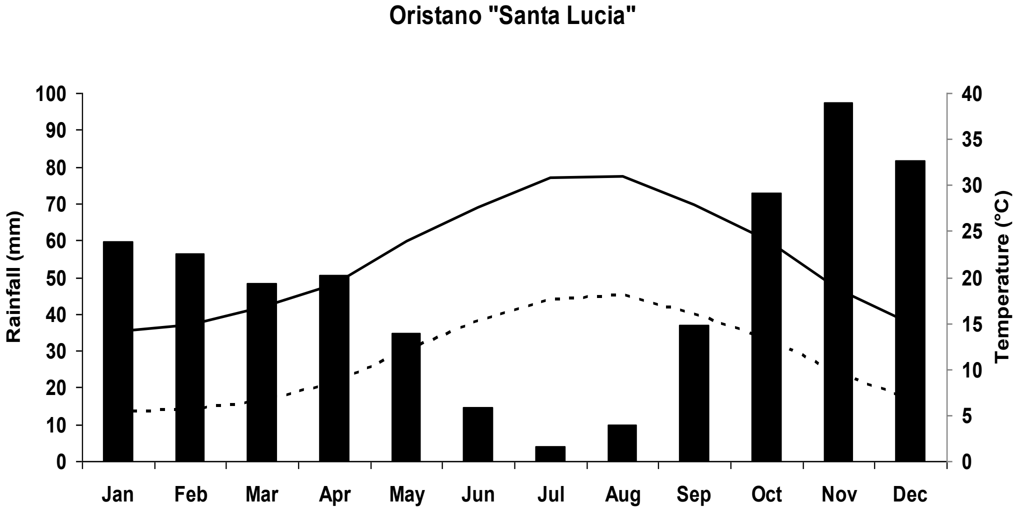


Figure 6. Fifty years (from 1 January 1959 to 31 December 2008) average values of rainfall (bars), maximum (solid line) and minimum (dashed line) temperatures. Rainfall values are 50 years average of monthly sums and temperature values are 50 years average of monthly means.

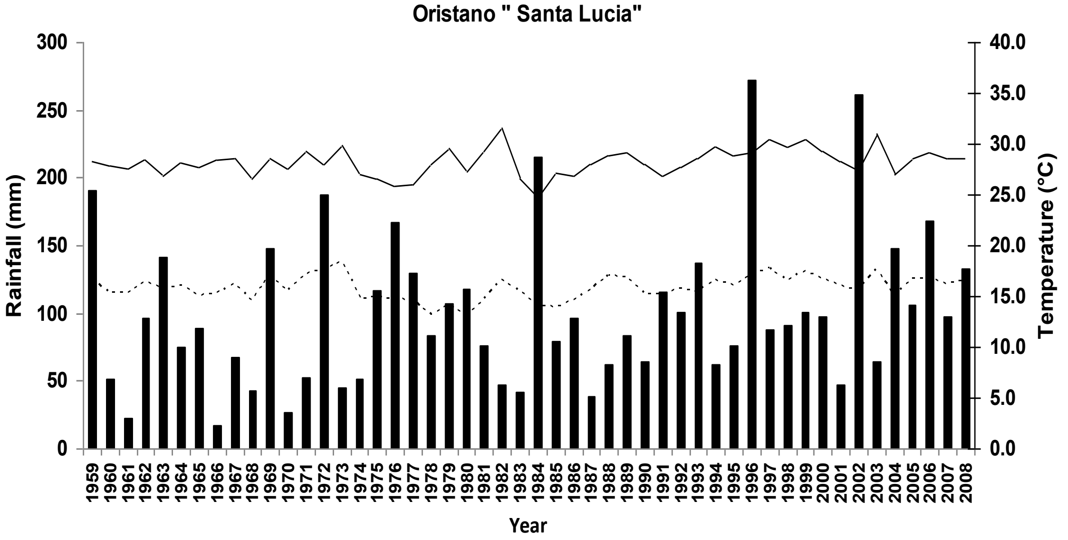


Figure 7. Fifty years seasonal (from 1 May 1959 to 30 September 2008) average values of rainfall (bars), maximum (solid line) and minimum (dashed line) temperatures. Rainfall values are 50 years average of seasonal sums and temperature values are 50 years average of seasonal means.

3.2 Agronomic management

3.2.1 Maize crops management

The maize cultivars planted were a Pioneer hybrid (PR31Y43) FAO class 700, in the year 2007 and a Frontal hybrid, FAO class 600, in 2008.

In May 2007 and in June 2008, a ripper was used to till the soil to a depth of 15 cm then, the seedbed was prepared with a rotary harrow (10 cm depth). The crops were sown on May 26, 2007, and on June 16, 2008, with a 75 cm row spacing, 7 plants m^{-2}. Weed control was accomplished using a commercial product containing mesotrione (3.39 %), S-metolachlor (28.23 %) and terbuthylazine (16.94 %), while for the pest control was used a product containing chlorpyrifos (75 %), for both maize crops growing seasons. Irrigation were made by sprinklers at the rates of about 6000 m^3 ha^{-1} for both seasons, in 22 and 18 applications in 2007 and

2008 respectively. The crops were harvested for silage, harvest was carried out on September 07, 2007 and on September 19, 2008.

3.2.2 Triticale crop management

The triticale cultivar planted was “Linea 140”, the field was prepared in October by a chisel-ploughing to a depth of 30 cm. The sowing was made in November 17, 2007, at depth of 3 cm and 15 cm distance between the rows. In order to avoid water stresses, on February and March 2008, two irrigation applications were made by sprinklers at the rates of 150 m^3 ha^{-1}. The crop was harvested for silage on May 9, 2008. Fertilizers and organic amendments rates, N content and application dates for all crops and seasons are reported in table 1.

3.3 Soil, plants, water, manure and slurry sampling

The soil samples were taken in May 2007, prior planting the maize crop, to determine the soil chemical properties to use as input in the simulation models. During the growing seasons of maize and triticale crops, at different growth stages, soil and plants samples were taken to determine the total N content, the Organic Carbon content, the nitrate N and ammonium N content of soil samples, the total N content and the biomass production of plants. A total of six sampling points were considered for the 4 ha field at each date of sampling. Eight soil depths were sampled with an increment of 10 cm for the first two layers and 20 cm for the other six layers, up to a total depth of 140 cm.

The plants situated in one meter of row length were removed from the field in order to be analyzed. In the course of the soil sampling a water table was detected at different depths, and samples of water in the soil profile were taken in order to determine the nitrate and ammonium N content.

Soil texture was determined using the modified pipette procedure for particle-size analysis (Indorante *et. al.,* 1990; Moshrefi, 1993), pH in water was determined with a pH meter (GLP 21, CRISON, 08328 Alella, Barcelona, Spain.) calibrated with pH 4.0 and 7.0 buffer solutions, Organic Carbon was measured using the Walkley-Black method (Walkley and Black, 1934), total N was determined using Kjeldahl method, nitrate N was determined using the Fox and Piekielek method (1978) based on the extraction method proposed by MacLean (1964), while ammonium N was determined using the colorimetric method proposed by Henzell *et al.* (1968) based on the Berthelot's reaction (1859). The available phosphorus in soil was determined with the Olsen method (Olsen *et. al.,* 1954) , the potassium was determined using a $BaCl_2$ and triethanolamine solution (Ministry of Agricultural and Forestry Policies, 1999). Soil water content and bulk density were estimated according to the method proposed by Ritchie *et al.* (1987). Some of the formulas used by Ritchie have been modified with the corrections proposed by Gijsman *et al.* (2002), the parameter SSAT (Volumetric soil water content in soil layer L at Saturation) has been calculated using the American Society of Agronomy method.

Manures and slurry samples and analysis, were made in collaboration with the *Department of Animal Sciences* of the University of Sassari. The samples were collected on April 2007 and May 2008, the manure sampling was carried out immediately after manure had been mixed, in order to avoid stratification, slurry samples were collected using a NISKIN bottle (80 cm of height, 7 cm of diameter), which is specific for sampling liquids in depth and is able to draw a column of liquid.

Soil, water, manure and slurry samples were immediately stored in a deep freeze at - 20°C until analysis.

Picture 3. Maize crop (Hybrid PR31Y43) in the year 2007.

Picture 4: Triticale crop ("Linea 140") in the year 2007.

Table 1. Fertilizers and organic amendments rates, N content and dates of distribution.

Date (dd/mm/yy)	Field	Fertilizers and amendments	Amount (q ha^{-1})	%N	Kg N ha^{-1}
12/05/2007	Field East (2 ha)	Manure	460 q ha^{-1}	0.74	340 Kg N ha^{-1}
12/05/2007	Field West (2 ha)	Slurry	880 q ha^{-1}	0.31	270 Kg N ha^{-1}
18/06/2007	Field 16 (4 ha)	Urea	1.5 q ha^{-1}	46	69 Kg N ha^{-1}
29/06/2007	Field 16 (4 ha)	Urea	3.0 q ha^{-1}	46	138 Kg N ha^{-1}
10/07/2007	Field 16 (4 ha)	Urea	1.5 q ha^{-1}	46	69 Kg N ha^{-1}
Total N maize 2007	**Field East (2 ha)**	**Manure + Urea**			**616 Kg N ha^{-1}**
Total N maize 2007	**Field West (2 ha)**	**Slurry + Urea**			**546 Kg N ha^{-1}**
20/10/2007	Field 16 (4 ha)	Slurry	400 q ha^{-1}	0.31	123 Kg N ha^{-1}
20/02/2008	Field 16 (4 ha)	Ammonium nitrate	2.5 q ha^{-1}	27	67.5 Kg N ha^{-1}
10/03/2008	Field 16 (4 ha)	Ammonium nitrate	1.0 q ha^{-1}	27	27 Kg N ha^{-1}
Total N Triticale 07/08	**Field 16 (4 ha)**	**Slurry + Amm. nitrate**			**217. 5 Kg N ha^{-1}**
21/05/2008	Field East (2 ha)	Manure	375 q ha^{-1}	0.53	200 Kg N ha^{-1}
21/05/2008	Field West (2 ha)	Slurry	800 q ha^{-1}	0.30	240 Kg N ha^{-1}
01/07/2008	Field 16 (4 ha)	Entec 46	3.0 q ha^{-1}	46	138 Kg N ha^{-1}
10/07/2008	Field 16 (4 ha)	Urea	1.0 q ha^{-1}	46	46 Kg N ha^{-1}
Total N maize 2008	**Field East (2 ha)**	**Manure + Urea**			**384 Kg N ha^{-1}**
Total N maize 2008	**Field West (2 ha)**	**Slurry + Urea**			**424 Kg N ha^{-1}**

3.4 Modelling approach

3.4.1 The cropping systems simulations models: overview

Simulation models can support quantitative and integrated analysis of agricultural systems. In fact, the time necessary in field experiments for testing all the possible alternative combinations of factors governing the plant-soil-atmosphere system is generally lengthy and expensive.

Moreover traditional agronomic experiments are conducted at particular points in time and space, making results site and season specific (Jones *et al.*, 2003). In the past years, model application has become increasingly important (Boote *et al.*, 1996; Donatelli *et al.*, 2002), in particular for studying the relations between agriculture and environment. Crop simulation models have the potential to integrate the effects of temporal and multiple stresses interaction on crop growth under different environmental and management conditions (Basso *et al.*, 2001).

Models can support strategic decisions, such as the definition of best crop management (e.g. Acutis *et al.*, 2000; Lewis *et al.*, 2003) and the development of sustainable farming systems (e.g. Shaffer *et al.*, 2000; Cabrera *et al.*, 2005); they can also help to make within-season management decisions, as predicting crop yields (e.g. Bannayan *et al.*, 2003) or evaluating replanting options (e.g. Heinger *et al.*, 1997).

In agricultural systems the identification of optimal management techniques for N fertilizers in the context of water protection from nitrate pollution and the estimation of nitrate loads to groundwater is a problem that can be effectively addressed with simulation models (e.g. Acutis *et al.*, 2000). Simulation models, after their calibration and evaluation in known situations, can help to quantify N losses both in real situations and in generated scenarios. This is particularly important for livestock farms, where animal N load can be relevant (e.g. Sacco *et al.*, 2003; Bechini and Castoldi, 2006).

3.5 The DSSAT Cropping System Model

The decision support system for agrotechnology transfer cropping system model (DSSAT-CSM) was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project (IBSNAT, 1993; Tsuji, 1998; Uehara, 1998; Jones *et al.*, 1998), to facilitate the application of crop models in a systems approach to agronomic research.

The DSSAT-CSM is a made of independent programs that operate together; crop simulation models are at its center. The DSSAT-CSM simulates growth, development and yield of a crop growing on a uniform area of land under given or simulated management as well as the changes in soil water, carbon, and N that take place under the cropping system over time.

The DSSAT-CSM has a main driver program, a land unit module and modules for the primary components that make up a land unit in a cropping system. The Primary modules are for weather, soil, plant, soil-plant-atmosphere interface, and management components.

The Land Unit Module provides the interface between the application driver (main program) and all of the components that interact in a uniform area of land (Jones *et al*., 2003).

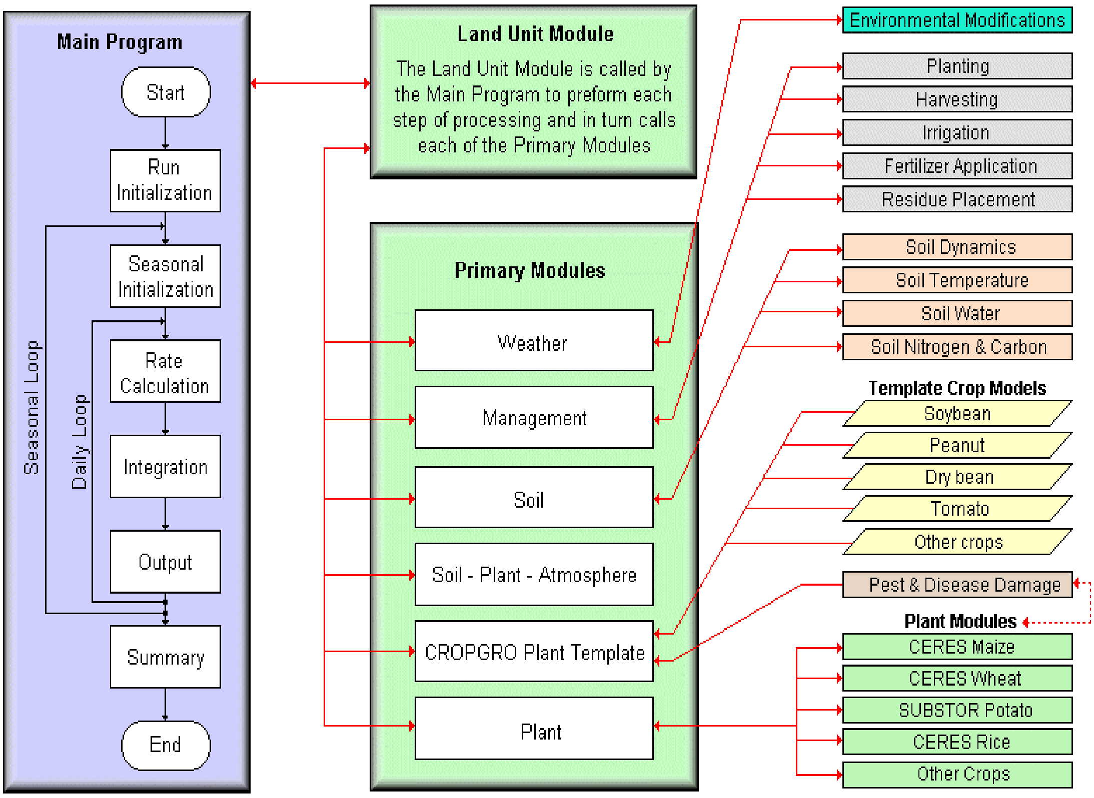


Figure 8. Overview of the components and modular structure of the DSSAT-CSM (Jones *et al.*, 2003)

3.6 Description of the DSSAT-CSM components

3.6.1 Weather module

The most important function of the Weather module is to read or generate daily weather data. It reads in daily weather values (maximum and minimum air temperatures, solar radiation and precipitation, relative humidity and wind speed), from the daily weather file (Jones *et al*, 2003). This module generates daily weather data using the WGEN (Richardson, 1981, 1985) or SIMMETEO (Geng *et al*., 1986, 1988) weather generators.

3.6.2 Soil module

The soil in the land unit consists of a number of vertical soil layers and the soil module combines information from four sub modules: soil water, soil temperature, soil carbon and nitrogen, and soil dynamics.

The soil dynamics module is designed to read-in soil parameters for the land unit and to modify them based on tillage, long-term changes in soil carbon, or other field operations. (Jones *et al*, 2003).

3.6.3 Soil water sub module

The soil water balance model developed for CERES-Wheat by Ritchie and Otter, (1985) was adapted for use by the DSSAT crop models (Jones and Ritchie, 1991; Jones, 1993; Ritchie, 1998). This model calculates the daily changes in soil water content by soil layer due to infiltration of rainfall and irrigation, vertical drainage, unsaturated flow, soil evaporation, and root water uptake processes. The soil surface conditions and layer-by-layer soil water holding and conductivity characteristics are described by soil parameters. The SCS method (Soil Conservations Service, 1972) is used to partition rainfall into runoff and infiltration, based on a ‘curve number’ that attempts to account for texture, slope, and tillage.

The modification to this method that was developed by Williams et al. (1984) is used in the model. (Jones *et al*, 2003).

3.6.4 Soil carbon and nitrogen balance sub module

The DSSAT-CSM has two options to simulate the soil organic matter (SOM) and N balance. The original SOM model in DSSAT v3.5 (Godwin and Jones, 1991; Godwin and Singh, 1998), based on the PAPRAN model of Seligman and Van Keulen (1981), was converted into a modular structure and retained in the new DSSAT-CSM. Additionally, a SOM module developed by Gijsman *et al*. (2002), based on the CENTURY model (Parton *et al*., 1988, 1994), is included in DSSAT-CSM.

The main differences are that the CENTURY-based module divides the SOM in more fractions, each of which has a variable C:N ratio and can mineralize or immobilize nutrients; it has a residue layer on top of the soil and the decomposition rate is texture dependent.

In both SOM modules, organic matter decomposition depends on soil temperature and water content. The N balance model simulates the processes of organic matter turnover with the associated mineralization and/or immobilization of N, nitrification, denitrification, hydrolysis of urea, ammonia volatilization, N plant uptake and translocation to the different organs during crop cycle. Transport of nitrate occurs at the same rate as the flow of water (Booltink *et al*., 1996).

3.6.5 Soil temperature sub module

The soil temperature model currently in the DSSAT-CSM was originally derived from the EPIC model (Williams *et al.*, 1984; Jones *et al.*, 1991). Soil temperature is computed from air temperature and a deep soil temperature boundary condition that is calculated from the average annual air temperature and the amplitude of monthly mean temperatures.

Soil temperature is used to modify plant processes (emergence) and SOM decomposition (Jones et al. 2003).

3.6.6 Soil-plant-atmosphere module (SPAM)

This module includes soil, plant and atmosphere inputs and calculates light interception by the canopy, potential evapotranspiration (ET), actual soil evaporation and plant transpiration. It also computes the root water uptake of each soil layer. The daily weather values as the same as all soil properties and current soil water content, by layer, are required as input.

3.6.7 Management module

The management module determines when field operations are performed by calling sub modules. Currently, these operations are planting, harvesting, applying inorganic fertilizer, irrigating and applying crop residue and organic material. Users specify whether any or all of the operations are to be automatic or fixed based on input dates or days from planting. Harvesting can occur on given dates, when the crop is mature, or when soil water conditions in the field are favorable for machine operation.

Irrigation and fertilization can be applied on specific dates with specified amount or can be controlled by the plant available water and the N stress variable from the Plant module. Crop residue and organic fertilizer, such as manure, is applied either at the start of simulation, after harvesting the crop or on fixed dates similar to inorganic fertilizer applications. (Jones *et al.*, 2003).

3.6.8 Plant module: CERES Maize and Wheat

The CERES (*Crop Environment Resource Synthesis*) model has been designed to simulate growth, soil water and temperature and soil N dynamics at a field scale for one growing season. Several CERES individual crop models (maize, wheat, sorghum, millet, barley, and rice) as well as potato (Hoogenboom *et al.*, 1999; Ritchie *et al.*, 1998; Singh *et al.*, 1998) are implemented in the DSSAT software (Jones *et al.*, 2003).

In this research the CERES-Maize and Wheat crop models have been used.

To run the model several input files must be compiled that contain information about the experiment site, soil, climate and genotype (Tsuji *et al.*, 1994). For these CERES models, the plant life cycle is divided into several phases, which are similar among the crops. Rate of development is governed by thermal time, or growing degree days (GDD), which is computed based on the daily maximum and minimum temperatures. The GDD required to progress from one growth stage to another are either defined as a user input, or are calculated internally based on user inputs and assumptions about duration of intermediate stages. The growth stages and the genotype coefficients for the DSSAT CERES-Maize and Wheat are listed in tables 2 and 3.

Table 2. Growth stages simulated by the DSSAT CERES-Maize and Wheat models.

Maize	Wheat
Germination	Germination
Emergence	Emergence
End of juvenile	Terminal spikelet
Floral induction	End ear growth
75% Silking	Beginning grain fill
Beginning grain fill	Maturity
Maturity	Harvest
Harvest	

Table 3. Genetic coefficients for the DSSAT CERES-Maize and Wheat models.

Maize	Wheat
P1: Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod.	**P1D:** Photoperiod sensitivity coefficient (% reduction/h near threshold)
P2: Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours).	**P1V:** Vernalization sensitivity coefficient (%/d of unfulfilled vernalization). Days at optimum vernalizing temperature required to complete vernalization.
P5: Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8°C).	**P5:** Grain filling (excluding lag) period duration, thermal time (°C.d).
G2: Maximum possible number of kernels per plant	**G1:** Kernel number per unit stem + spike weight at anthesis (#/g)
G3: Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day).	**G2:** Standard kernel size under optimum conditions (mg).
PHINT: Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	**G3:** Standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (g).
	PHINT: Phyllochron interval.

Daily plant growth is computed by converting daily intercepted photosynthetically active radiation (PAR) into plant dry matter using a crop-specific radiation use efficiency parameter. Light interception is computed as a function of LAI, plant population, and row spacing. The amount of new dry matter available for growth each day may also be modified by the most limiting of water or N stress, and temperature, and is sensitive to atmospheric CO_2 concentration (Jones *et al*., 2003).

3.7 The SALUS model

3.7.1 The SALUS model overview

The SALUS (*System Approach to Land Use Sustainability;* Basso *et al*., 2006) program is designed to model continuous crop, soil, water and nutrient conditions under different management strategies for multiple years. The program will simulate plant growth and soil conditions every day (during growing seasons and fallow periods) for any time period when weather sequences are available. For any simulation run, a number of different management scenarios can be run simultaneously and all main components of the crop-soil-water model (management practices, water balance, soil organic matter (SOM), N and P dynamics, heat balance, plant growth and plant development) are executed daily. The water balance considers surface runoff, infiltration, surface evaporation, saturated and unsaturated soil water flow, drainage, root water uptake, soil evaporation and transpiration.

The SOM and nutrient model simulates OM decomposition, N mineralization and formation of NH_4^+ and NO_3^-, N immobilization, gaseous N losses and three pools of phosphorous. The development and growth of plants considers the environmental conditions to calculate the potential rates of growth for the plant. This growth is then reduced based on water and N limitations.

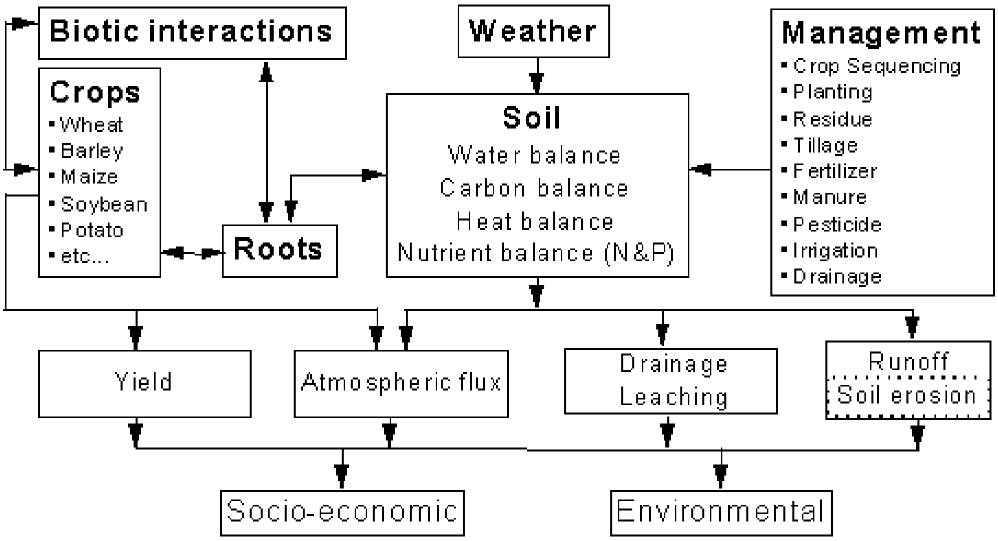


Figure 9. Diagram of the component of SALUS

3.7.2 Module descriptions and derivations

The biophysical model is composed of three main structural components: crop growth modules; SOM and nutrient cycling module; soil water balance and temperature module. The crop growth modules are derived from the CERES (Ritchie and Otter, 1985) and IBSNAT (Jones and Ritchie, 1991), family of crop production models that were originally developed for single year, monoculture simulations. The crop growth algorithms from these were extracted and restructured into crop growth modules that are linked to the soil water, nutrient and management sub-models. Current operational crop growth modules include maize, wheat, barley, sorghum and millet, a generic grain legume module (e.g., soybean, dry beans) and alfalfa. The soil organic matter (SOM) and N module is derived from the CENTURY model (Parton et al. 1987), with a number of modifications incorporated. The model simulates organic matter and N mineralization/immobilization from three SOM pools (active, slow and passive) which vary in their turnover rates and characteristic C:N ratios (figure 10).

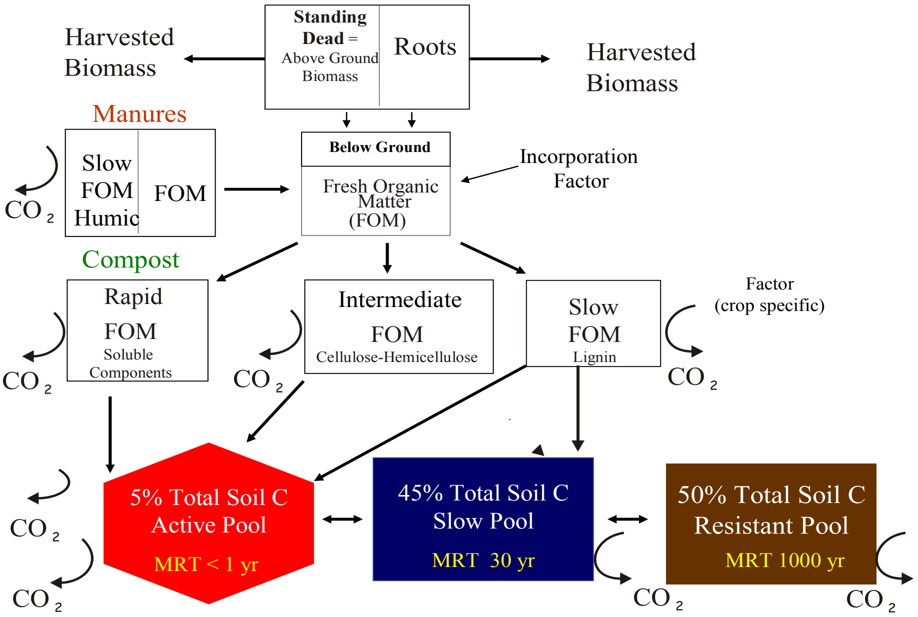


Figure 10. SALUS flows of organic matter into soil carbon pools (Basso and Ritchie, 2010)

There are two crop residue/fresh organic matter pools (structural and metabolic), for representing recalcitrant and easily decomposable residues, based on residue lignin and N content. Decomposition and N mineralization rates for the different pools are influenced by soil temperature and moisture, soil texture and tillage intensity (as well as pool C:N ratio for N mineralization). Several modifications were made to adapt the model for use with daily time-step crop growth routines. The original Century model operates on a monthly time step and therefore, rate constants were recalibrated to correct for the difference in integration interval (from monthly to daily). A surface active SOM pool associated with the surface residue pools was added to better represent conservation tillage systems and perennial crops. An algorithm was developed which determines the initial fraction of total organic matter C and N in each of the three SOM pools (for model initialization), as a function of soil texture, type of original native vegetation and time under cultivation, based on a steady-state analytical solution of the decomposition equations (Paustian 1992). The soil water balance module is based on that used in the CERES models but incorporates a major revision in calculating infiltration and runoff. In SALUS, a time-to-ponding (TP) concept is used to replace the previous runoff and infiltration calculations which were based on SCS runoff curve numbers. Briefly, time-to-ponding curves relate rainfall intensity to infiltration rate and define the point at which cumulative rainfall intensity exceeds the infiltration capacity of the soil (White *et al.* 1989) at which time water ponding in micro-depressions in the soil surface occurs.

After ponding begins, infiltration is equal to the amount predicted by the TP curve as long as rainfall rate exceeds the infiltration capacity. When rainfall rate becomes less than the infiltration capacity, rainfall plus surface ponded water are infiltrated until the amount ponded is depleted. The main management-influenced parameter controlling the TP curve is the saturated hydraulic conductivity at the soil surface, which is varied as a function of tillage, soil compaction and surface residue amounts (Dadoun 1993).

3.7.3 User interface

SALUS provides a user interface consisting of an input and output files management; and an interactive control system. Input and output files use the DSSAT formats. These standard files allow the user to create data files with existing programs from DSSAT and the output files can be used with the graphics and analysis programs written by DSSAT. The input files contain information to initialize the model (e.g., physical and chemical properties, soil water contents and N concentrations) and supply driving variables (i.e., time series of weather and management practices). The output files contain summaries of important model variables such as crop yield, crop developmental stages, N uptake, nitrate leaching, water drainage, runoff, soil organic C and N levels, irrigation water used and fertilizer applied. All model state variables and important process rates are stored continuously and can be output in graphical form.

3.8 Models calibration and validation

3.8.1 Background

Models calibration requires data sets with all information needed as input to run the model (e.g., crop management, aerial and soil environments, and genotype characteristics), together with some data on plant performance or soil conditions (Tsuji *et al.* 1998). Evaluation involves comparison of the outputs of a fully calibrated model to real data and a determination of suitability for an intended purpose (Lemon, 1977).

The aim of evaluation is to determine the value of a crop model, with respect to the planned use of the model. A first approach to the evaluation of model results is to compare model results with data.

Evaluation concerns how well the model reproduces input-output relationships. In the literature, one often encounters the term validation rather than evaluation.

A rather common definition is that validation concerns determining whether a model is adequate for its intended purpose or not. When the model is used to test an hypothesis concerning how the systems under study function, the user wish to test the hypothesis that the processes as described by the model are the same to the way the real word functions. In this case is reasonable to use the term validation rather than evaluation. The objective of a model is frequently prediction, another possible objective is to use the model as an aid to decision-making (Wallach *et al.*, 2006); the latter was one of the objective of this research.

3.8.2 Model data-set

The data-set collected in the years 2007 and 2008 was used to calibrate and validate the DSSAT-CSM for the maize crops in the specific conditions of the NVZ of Arborea. The DSSAT-CSM doesn’t contain the triticale crop so, the model was tested using the wheat crop instead of triticale.

The complete data-set used to ran the model’s experiments includes**:** weather data (daily maximum and minimum temperature, rainfall, solar radiation), soil data (soil surface and profile information: water holding characteristics, organic matter**,** P, organic C, texture, pH, potassium, total N, nitrate and ammonium N content at different depths over time), crop management (seedbed preparation and planting geometries, irrigation and water management, fertilizer management, organic residue applications, tillage operations, harvest management).

3.8.3 Genetic coefficients estimation

In this research, the estimation of the genetic parameters was made using a Genetic Coefficient Calculator (GENCALC), a software designed to estimate genetic coefficients for models in the DSSAT system (Hunt *et al.*, 1993). As a parameter estimation method, GENCALC needs an initial value for each parameter to begin calculations. It then fits a genetic coefficients to each of the observed values provided. The algorithm searches the output file and, based on the differences between predicted and actual values, decides whether to increase or decrease the coefficient being considered

(Hunt, 1997). When GENCALC finds a good fit to each observation, it averages the coefficients and calculates the coefficient of variation (CV). Based on the new candidate parameters, the user repeats the process. The search finishes when the user accepts the parameters based on a low CV. The genotype coefficients for the DSSAT CERES-Maize and Wheat have been described in the chapter 2; the values of the genetic coefficients used in this study are listed in tables 4 and 5.

Table 4: Genetic coefficients Maize 2007 and 2008 in the DSSAT Experiments

Genetic coefficients	P1	P2	P5	G2	G3	PHINT
Maize 2007	264.8	0.000	734.3	499.8	13.30	41.09
Maize 2008	297.2	0.000	572.8	290.0	16.50	50.50

Table 5: Genetic coefficients Triticale 2007-2008 in the DSSAT Experiments

Genetic coefficients	P1V	P1D	P5	G1	G2	G3	PHINT
Triticale (Wheat) 2007-2008	0.00	68.5	869.6	25.0	40.0	1.50	80.0

3.8.4 Statistics measures of agreement between measured and calculated values

The basic measure for quantify the agreement between model and observations is their difference, noted: $D_i = Y_i - \hat{Y}_i$, where Y_i is the measured value for situation i and $\hat{Y}_i$ is the corresponding value calculated by the model. An easy way to summarize the D_i values for several situations is to calculate their average, also known as model bias: Bias = $1/N \; \Sigma \; D_i$, where N is the total number of situations.

The *bias* measures the average difference between measured and calculated values. When, on the average, the model under-predicts, the *bias* is positive, and on the other hand if, on the average, the model over-predicts the *bias* is negative. Bias alone, however, is not sufficient as a summary of model errors. A bias value near to zero may be the effect of very small errors in all situations, or alternatively of large errors that approximately cancel each other between under and over prediction.

There are two measures of agreement that remove the problem of compensation between under and over prediction. The most widely used is the *mean squared error*, defined as: $MSE = (1/N)\ \Sigma\ (D_i)^2$. Often it is opportune to work with the square root of MSE, called *root mean squared error*; $RMSE = \sqrt{MSE}$. The advantage is that RMSE has the same units as Y and thus is easier to understand (Wallach *et al.* 2006). In this research, the RMSE was used to compares model predictions with observed data.

3.8.5 Selection criteria of seasonal simulation scenarios using DSSAT

In order to evaluate the values of yields and N leached considering a long term simulation made by fifty years weather record (1959 – 2008), the data-set related to the maize crop cultivated in the growth season 2007 (from May to September), has been implemented in a DSSAT-CSM seasonal file. The aim of these simulations were to determine the best management strategy for irrigation and nitrogen management that allow to minimize the amount of N loss by leaching maintaining a sufficient level of yield.

Different seasonal simulation scenarios have been created with DSSAT-CSM through the combination of five N management and three irrigation strategies. The N management strategies have been determined considering the following criteria: type and amount of N fertilizers (mineral and organic) used by the farmers in the experimental field in the years 2007, the measured N plants uptake during the 2007 growing season (276 Kg N ha^{-1}) and the PUA, as mentioned before, in conformity with the P.U.A. a maximum of 170 kg ha^{-1} year^{-1} from animal manures can be spread per hectare per year in vulnerable areas. The different N fertilization and irrigation management strategies created are summarized below:

Nitrogen management strategies:

1. **Conventional Fertilization (N CONV.);**

- **616 Kg N ha^{-1}: 340 Kg N ha^{-1} from manure and 276 Kg N ha^{-1} from Urea.**
- **546 Kg N ha^{-1}: 270 Kg N ha^{-1} from slurry and 276 Kg N ha^{-1} from Urea.**

2. **N 0;**

- **No N fertilization;**

3. **P.U.A. 1;**

- **276 Kg N ha^{-1} (86 Kg N ha^{-1} from organic fertilizers and 190 Kg N ha^{-1} from Urea);**

4. **Mineral fertilization (N MIN.);**

- **276 Kg N ha^{-1} from Urea;**

5. **P.U.A. 2;**

- **276 Kg N ha^{-1} (170 Kg N ha^{-1} from organic fertilizer and 106 Kg N ha^{-1} from Urea);**

Irrigation management:

Conventional Irrigation: Irrigation type, volumes and schedule applied by the farmers in the experimental field in the years 2007 (Sprinkler, 6000 m^3 ha^{-1} in 22 applications);

Automatic Irrigation: Irrigation volumes and schedule controlled automatically by the model with relation to the plant extractable soil water. If soil available water dropped below a specified fraction of water holding capacity (50%) in an irrigation management depth (30 cm), an irrigation event was triggered to refill the profile to the management depth.

Minimal Irrigation: This amount (380 mm), was obtained reducing the irrigation volumes and the number of applications until a value that allowed the crops to reach the harvest maturity for all the fifty years considered in the simulations.

3.8.6 Statistic methodologies

The averages values of biomass production and nitrate leaching resulting from the DSSAT-CSM long term simulations have been compared by the t test (P = 0.05), (Steel and Torrie,1980). Averages indicated as different in the results and discussion section have been compared with this test.

3.9 SALUS model simulations

The simulation of crop rotation allows to achieve a more precise information about the N leaching compared to a seasonal simulation of a single crop because leaching occurs continuously throughout the year.

The seasonal simulation procedure quantifies leaching only till the end of the growing season. It is known that most of the leaching occurs during the autumn/winter period and/or when the crop is not present (Basso and Ritchie, 2005). For these specific reasons the SALUS model, which is based on a rotational simulation procedure, was selected to assess the leaching potentials under the conventional management strategies adopted by farmers in the study site (see materials and methods, paragraph 3.2).

SALUS model requires the same data input of DSSAT-CSM, thus soil, weather, management and crop genotypes were the same used for the seasonal analysis carried out with DSSAT-CSM. The SALUS rotational simulations were performed using the following steps:

- A first set of rotational simulations were carried out for the 2007 and 2008 experiments, with the goal of comparing measured and simulated results. For these simulations the soil N initial conditions were set using the measured values in the beginning of the field trial.

- A second set of rotational simulations were carried out for a long term assessment of the two treatments in comparisons. The fifty years simulation started in 1959 assuming low N content

(19 Kg N ha^{-1} for the whole soil depth) in the soil to represent the poor organic matter and low N content of sandy soils.

These simulations were selected to determine the effect of yearly application of manure and slurry on soil inorganic N and cumulative N leaching. Moreover this scenario allowed to validate the SALUS model with the measured initial conditions of 2007.

- An additional long term rotational simulation series was performed using the initial conditions measured in 2007 with the goal of evaluating the soil inorganic N content and the cumulative N leaching for manure and slurry applications for fifty years.

- Finally a long term rotational simulation runs were carried out applying 276 Kg N ha^{-1} of urea as the only source of N input to compare its effect on leaching and inorganic soil N with the conventional management strategies.

4. RESULTS AND DISCUSSION

4.1 Field measurements results

4.1.1 Soil samples analysis results

The results of the physical, mechanical and chemical analysis of the soil samples collected in May 2007 are summarized in the tables 6 and 7 at the end of the chapter. The soil had an average stones percentage of about 2%, the content of clay was about 3.3% up to 0.6 m depth and less (about 1%) in the layers between 0.8 and 1.4 m depths. The soil was characterized by an high content of sand, about 93%, for the first four layers (up to 0.6 m) and 97% in the other layers, with a maximum of 98.4% at 1.0 m depth.

The bulk density was, on average, 1.48 g cm^{-3}, from 0 to 0.4 m depths, 1.57 at 0.6 m depth and 1.67 g cm^{-3} in the deeper layers. The soil profile differences among the percentages of clay and sand, bulk density and available water, from lower to higher depths, are probably due to the continuous use of organic amendments (manure and slurry), this practices presumably had an influence in some chemical characteristics of the soil. The pH of the soil was 7.5, the percentages of total N and soil organic matter showed decreasing values from lower to higher depths.

The soil organic matter content was 4.50 % in the first 0.10 m, 1.86 % at 0.60 m depth, showing the lowest value in the profile (0.28 %) at 1.40 m depth. The total N content was 0.22 % in the first 0.10 m, 0.09 % at 0.60 m depth and reached the minimum value in the profile (0.02 %) at 1.40 m depth. The nitrate and ammonium N content were, on average, 22.6 p.p.m. and 24.6 p.p.m. respectively. The nitrate and ammonium N soil content during the growing seasons of maize and triticale crops, in the years 2007 and 2008, are summarized in table 8 at the end of the chapter.

Table 8 contains the average values of nitrate and ammonium N in the entire soil profile (from 0 to 1.40 m depths), but there were large differences between the layers, in particular for the nitrate N.

In the manure treatment, the maximum value of nitrate N was 627.3 p.p.m. at 0.10 m depth, on September 2008, while the minimum value was 0.85 p.p.m. at 1.40 m depth on July 2007. In the slurry treatment, the maximum value of nitrate N was 477.6 p.p.m. at 0.10 m depth, on September 2008, while the minimum value was 8.90 p.p.m. at 0.60 m depth on September 2007. The soil had, on average, a C/N ratio of 11.6, and showed a very high content of phosphoric anhydride (P_2O_5), 120 p.p.m in the first 0.40 m, and potassium oxide (K_2O); 482 p.p.m. at 0.40 m depth.

4.1.2 Plants samples analysis results

Biomass production and crops N content during the growing seasons are summarized in table 9. The biomass production and the N uptake increased during the growing seasons and, at the harvest dates of the maize crop in 2007 were 25.97 t ha^{-1} and 275.6 Kg ha^{-1} respectively; whereas for the maize crop in 2008 were 24.67 t ha^{-1} and 193.47 Kg ha^{-1} and for the triticale crop were 6.87 t ha^{-1} and 94.5 Kg ha^{-1}. The N content (%) of biomass showed decreasing values during the growing seasons, the reduction of the N percentage is common in all the cultivate crops, and the determined values are in agreement with the data reported by Havlin *et al.* (1999).

4.1.3 Water samples analysis results

The NO_3^- and NH_4^+ concentrations and the water table depths during the growing seasons are summarized in table 10. The nitrate N concentrations and the water table depths varied widely between the maize and the triticale crops growing seasons, in fact, from May to September 2007 the NO_3^- water content was, on average, 36.8 p.p.m.; from October 2007 to May 2008 was, on average, 216.4 p.p.m.; with a maximum of 335.5 p.p.m. on March 13th, 2008; while from July to September 2008 was 178.8 p.p.m.

The water table depth was 0.85 m at the first sampling date on May 2007 and 0.79 m at the last sampling date on September 2008, and reached a minimum depth on July 2008 when was 0.59 m and a maximum depth of 1.28 m on October 2007. The measured NH_4^+ concentrations were widely lower than the NO_3^- concentration, and varied from a minimum of 0.011 p.p.m. on June 2007 to a maximum of 19.9 p.p.m., on July 2008.

4.1.4 Manure and slurry samples analysis results

The manure and slurry samples collected in the years 2007 and 2008 were analyzed in order to determine the total N concentration (%).

The N concentrations of manure samples were, on average, 0.74 % for the samples collected in 2007, and 0.53 % for the samples of 2008.

The N concentration of slurry samples was 0.31 % in both years.

Table 6: Soil samples physical - mechanical and chemical analysis results (average values and standard errors)

Depths (cm)	Samples (n°)	Stones > 2 mm (%)	Clay < 0.002 mm (%)	Silt (0.02-0.002 mm) (%)	Sand (2 - 0.02 mm) (%)	Bulk density (g cm^{-3})	pH
10	4	**1.5** ± 0.4	**3.3** ± 0.2	**3.3** ± 1.1	**93.4** ± 1.3	**1.45** ± 0.024	**7.2** ± 0.15
20	4	**1.6** ± 0.4	**3.2** ± 0.1	**3.3** ± 1.0	**93.6** ± 1.1	**1.50** ± 0.013	**7.4** ± 0.16
40	4	**1.3** ± 0.4	**3.6** ± 0.6	**3.8** ± 0.8	**92.5** ± 0.4	**1.48** ± 0.021	**7.4** ± 0.08
60	4	**2.1** ± 0.7	**3.0** ± 0.3	**3.6** ± 0.7	**93.3** ± 1.0	**1.57** ± 0.003	**7.3** ± 0.22
80	4	**2.7** ± 0.6	**1.0** ± 0.1	**1.5** ± 0.4	**97.5** ± 0.4	**1.65** ± 0.004	**7.6** ± 0.23
100	4	**3.4** ± 0.4	**0.6** ± 0.1	**0.9** ± 0.2	**98.4** ± 0.3	**1.67** ± 0.003	**7.6** ± 0.16
120	4	**2.2** ± 0.7	**0.8** ± 0.5	**1.5** ± 0.7	**97.8** ± 1.1	**1.68** ± 0.008	**7.8** ± 0.13
140	4	**1.6** ± 0.6	**1.6** ± 0.7	**1.8** ± 1.1	**96.6** ± 1.8	**1.67** ± 0.012	**7.7** ± 0.06

Table 7: Soil samples chemical analysis results (average values and standard errors).

Depths (cm)	Samples (n°)	Total N (%)	NO_3^- (ppm)	NH_4^+ (ppm)	S.O.M. (%)	C/N	P_2O_5 (ppm)	K_2O (ppm)
10	4	**0.22** ± 0.030	**37.2** ± 1.7	**46.2** ± 1.8	**4.5** ± 0.5	**12** ± 0.4	**122.7** ± 34.2	**326.3** ± 34.1
20	4	**0.17** ± 0.014	**30.4** ± 1.3	**38.7** ± 1.9	**3.3** ± 0.3	**12** ± 0.5	**106.4** ± 33.6	**400.3** ± 50.9
40	4	**0.18** ± 0.012	**29.2** ± 1.3	**42.9** ± 2.0	**3.6** ± 0.5	**11** ± 1.4	**130.5** ± 14.8	**481.6** ± 145.9
60	4	**0.09** ± 0.005	**28.7** ± 1.3	**26.9** ± 1.9	**1.9** ± 0.1	**12** ± 0.8	**65.6** ± 1.9	**299.2** ± 63.9
80	4	**0.04** ± 0.000	**23.6** ± 1.5	**10.1** ± 0.3	**0.8** ± 0.1	**11** ± 1.2	**12.5** ± 1.0	**200.5** ± 21.1
100	4	**0.03** ± 0.003	**10.1** ± 0.9	**9.6** ± 0.4	**0.5** ± 0.1	**11** ± 0.9	**10.3** ± 2.2	**142.7** ± 15.7
120	4	**0.02** ± 0.003	**9.4** ± 1.3	**13.5** ± 0.7	**0.4** ± 0.1	**13** ± 1.7	**7.3** ± 1.6	**157.1** ± 31.7
140	4	**0.02** ± 0.003	**12.1** ± 1.5	**9.2** ± 0.5	**0.3** ± 0.1	**12** ± 3.1	**7.0** ± 1.6	**149.9** ± 30.8

Table 8: Nitrate and ammonium N soil content during the growing seasons of maize and triticale crops (average values and standard errors).

Sampling dates (mm/dd/yy)	Treatments	Samples (n°)	Depths (m)	NO_3^- (p.p.m.)	NH_4^+ (p.p.m.)
06/29/2007	manure	3	0 – 1.40	**79.5** ± 29.9	**5.4** ± 2.8
06/29/2007	slurry	3	0 – 1.40	**81.4** ± 7.6	**3.1** ± 1.1
07/24/2007	manure	3	0 – 1.40	**55.2** ± 4.3	**3.2** ± 0.3
07/24/2007	slurry	3	0 – 1.40	**120.6** ± 3.5	**2.9** ± 0.2
09/07/2007	manure	3	0 – 1.40	**57.5** ± 8.2	**6.0** ± 2.2
09/07/2007	slurry	3	0 – 1.40	**40.2** ± 7.8	**10.1** ± 0.9
10/10/2007	manure	3	0 – 1.40	**69.2** ± 17.4	**14.7** ± 3.6
10/10/2007	slurry	3	0 – 1.40	**58.7** ± 6.9	**7.9** ± 0.9
01/08/2008	manure	3	0 – 1.40	**88.8** ± 25.6	**19.2** ± 3.6
01/08/2008	slurry	3	0 – 1.40	**62.3** ± 9.1	**14.5** ± 1.8
02/07/2008	manure	3	0 – 1.40	**86.6** ± 16.4	**18.0** ± 4.4
02/07/2008	slurry	3	0 – 1.40	**89.9** ± 18.0	**18.0** ± 6.7
03/13/2008	manure	3	0 – 1.40	**104.3** ± 8.5	**52.6** ± 9.4
03/13/2008	slurry	3	0 – 1.40	**86.3** ± 8.9	**40.7** ± 0.2
05/07/2008	manure	3	0 – 1.40	**54.9** ± 8.7	**19.5** ± 4.9
05/07/2008	slurry	3	0 – 1.40	**61.8** ± 9.9	**19.9** ± 4.9
07/04/2008	manure	3	0 – 1.40	**52.2** ± 10.7	**44.4** ± 3.1
07/04/2008	slurry	3	0 – 1.40	**68.6** ± 9.5	**52.8** ± 10.8
07/22/2008	manure	3	0 – 1.40	**104.3** ± 17.3	**76.0** ± 33.7
07/22/2008	slurry	3	0 – 1.40	**124.4** ± 23.7	**102.3** ± 40.3
08/19/2008	manure	3	0 – 1.40	**107.1** ± 54.3	**94.2** ± 31.9
08/19/2008	slurry	3	0 – 1.40	**75.72** ± 28.46	**31.0** ± 7.0
09/18/2008	manure	3	0 – 1.40	**48.93** ± 13.99	**9.5** ± 4.3
09/18/2008	slurry	3	0 – 1.40	**53.41** ± 11.23	**13.9** ± 0.9

Table 9: Biomass, N content and N uptake during the growing seasons of maize and triticale crops (average values and standard errors).

Sampling dates (mm/dd/yy)	Samples (n°)	Biomass (t ha^{-1})	N Content (%)	N Uptake (kg ha^{-1})
Maize				
06/29/2007	**6**	**1.52** ± 0.08	**3.11** ± 0.075	**46.9** ± 1.94
07/24/2007	**6**	**7.65** ± 0.45	**1.96** ± 0.106	**148.8** ± 8.34
09/07/2007	**6**	**25.97** ± 1.91	**1.06** ± 0.036	**275.6** ± 17.46
Triticale				
02/07/2008	**6**	**1.21** ± 0.15	**3.78** ± 0.158	**44.9** ± 4.25
03/13/2008	**6**	**3.06** ± 0.33	**2.75** ± 0.170	**82.4** ± 7.59
05/07/2008	**6**	**6.87** ± 0.58	**1.36** ± 0.070	**94.5** ± 10.97
Maize				
07/04/2008	**6**	**0.05** ± 0.01	**4.88** ± 0.158	**2.5** ± 0.31
07/22/2008	**6**	**1.67** ± 0.12	**3.55** ± 0.056	**59.3** ± 3.86
08/19/2008	**6**	**10.39** ± 1.00	**1.38** ± 0.054	**141.3** ± 9.65
09/18/2008	**6**	**24.67** ± 1.01	**0.79** ± 0.045	**193.5** ± 11.74

Table 10: Nitrate and ammonium N content in the water table samples during the growing seasons of maize and triticale crops (average values and standard errors).

Sampling dates (mm/dd/yy)	Samples (n°)	Water table depth (cm)	NO_3^- (ppm)	NH_4^+ (ppm)
05/10/2007	**4**	**85** ± 3.1	**46.0** ± 18.0	**0.93** ± 0.150
06/29/2007	**6**	**105** ± 2.9	**34.9** ± 5.3	**0.01** ± 0.002
07/24/2007	**6**	**71** ± 5.6	**36.1** ± 5.9	**0.02** ± 0.005
09/07/2007	**6**	**96** ± 4.5	**30.0** ± 7.4	**0.02** ± 0.002
10/10/2007	**5**	**128** ± 4.2	**77.0** ± 42.5	**10.58** ± 1.850
01/08/2008	**5**	**99** ± 5.0	**195.8** ± 55.3	**2.30** ± 0.351
02/07/2008	**6**	**103** ± 5.0	**165.5** ± 38.7	**1.30** ± 0.731
03/13/2008	**6**	**93** ± 4.5	**335.5** ± 72.0	**3.92** ± 3.270
05/07/2008	**6**	**94** ± 4.8	**308.0** ± 41.7	**1.30** ± 0.560
07/04/2008	**6**	**59** ± 4.5	**254.6** ± 54.4	**3.80** ± 0.860
07/22/2008	**6**	**85** ± 6.7	**313.3** ± 61.3	**19.90** ± 1.600
08/19/2008	**5**	**78** ± 3.8	**80.8** ± 36.8	**2.40** ± 0.950
09/18/2008	**6**	**79** ± 2.5	**66.6** ± 40.7	**1.50** ± 0.300

4.2 DSSAT-CSM Maize crop experiments results

The model simulated well the anthesis date for both treatments in the two years considered (observed: 65 days after planting; simulated: 66 days after planting for the maize crop in 2007; observed: 64 days after planting; simulated: 65 days after planting in 2008). The tops weight at harvest maturity in 2007 and in 2008 has been underestimated by the model for both treatments, in the 2007 was: (treatment 1 (manure): observed: 25048 Kg ha^{-1}, simulated: 23428 Kg ha^{-1}; treatment 2 (slurry): observed: 26898 Kg ha^{-1}, simulated: 23698 Kg ha^{-1} whereas in 2008 were: treatment 1 (manure):observed: 24909 Kg ha^{-1}, simulated: 17833 Kg ha^{-1}; treatment 2 (slurry): observed: : 24436 Kg ha^{-1}, simulated 18055 Kg ha^{-1}.

The variables tops weight and tops N have been slightly underestimated by the model for both treatments in the years 2007 and 2008.

The model underestimated the total soil NO_3^- content for both treatments in both years, the only value that has been overestimated by the model is the total soil NO_3^- content of the 137th day after the start of simulation in the treatment 1 in the 2008 maize experiment. The differences between measured and simulated values is probably due to the fact that in the *"Nitrates Vulnerable Zone"* of Arborea in the last seventy years the farmers, to improve the quality and quantity of harvest, have used a large amount of compounds rich of N like urea, manure and slurry that have increased the quantity of nitrates absorbed by the ground.

The tables 11-14 summarize the output files of the DSSAT-CSM experiments concerning the maize crops in the year 2007 and 2008.

Table 11. Observed and simulated total soil NO_3^- for the maize crop in 2007.

Treatments	Variable	Days after start of simulation	Measured values (Kg ha^{-1})	Simulated values (Kg ha^{-1})
1) Field East(manure)	Total soil NO_3^-	51	1267.0	777.7
1) Field East(manure)	Total soil NO_3^-	76	878.4	818.3
1) Field East(manure)	Total soil NO_3^-	120	968.9	535.6
2) Field West (slurry)	Total soil NO_3^-	51	1323.0	848.1
2) Field West (slurry)	Total soil NO_3^-	76	1925.0	772.3
2) Field West (slurry)	Total soil NO_3^-	120	685.5	413.8

Table 12. Observed and simulated tops weight and tops N for the maize crop in 2007.

Treatments	Variable	Days after planting	Measured Values (Kg ha-1)	Simulated values (Kg ha-1)
1) Field East (manure)	Tops weight	34	1435	1060
1) Field East (manure)	Tops weight	59	7682	8307
1) Field East (manure)	Tops weight	103	25048	23428
2) Field West (slurry)	Tops weight	34	1595	1060
2) Field West (slurry)	Tops weight	59	7620	8561
2) Field West (slurry)	Tops weight	103	26898	23698
1) Field East (manure)	Tops nitrogen	34	46.0	36.0
1) Field East (manure)	Tops nitrogen	59	137.0	195.2
1) Field East (manure)	Tops nitrogen	103	278.7	260.5
2) Field West (slurry)	Tops nitrogen	34	47.8	36.0
2) Field West (slurry)	Tops nitrogen	59	260.3	263.4
2) Field West (slurry)	Topsnitrogen	103	270.5	267.8

Table 13. Observed and simulated total soil NO_3^- for the maize crop in 2008.

Treatments	Variable	Days after start of simulation	Measured values (Kg ha^{-1})	Simulated values (Kg ha^{-1})
1) Field East (manure)	Total soil NO_3^-	61	978.6	854.4
1) Field East (manure)	Total soil NO_3^-	79	1713.0	942.6
1) Field East (manure)	Total soil NO_3^-	107	1702.9	842.3
1) Field East (manure)	Total soil NO_3^-	137	796.2	1078.0
2) Field West (slurry)	Total soil NO_3^-	61	1137.3	830.8
2) Field West (slurry)	Total soil NO_3^-	79	2012.0	728.0
2) Field West (slurry)	Total soil NO_3^-	107	1217.6	329.7
2) Field West (slurry)	Total soil NO_3^-	137	909.1	308.1

Table 14. Observed and simulated tops weight and tops N for the maize crop in 2008.

Treatments	Variable	Days after planting	Measured values (Kg ha^{-1})	Simulated values (Kg ha^{-1})
1) Field East (manure)	Tops weight	18	50.9	108.0
1) Field East (manure)	Tops weight	36	1636.0	1295.0
1) Field East (manure)	Topsweight	64	9623.0	9028.0
1) Field East (manure)	Tops weight	94	24909.0	17833.0
2) Field West (slurry)	Topsweight	18	52.2	108.0
2) Field West (slurry)	Tops weight	36	1711.0	1295.0
2) Field West (slurry)	Tops weight	64	11153.0	9235.0
2) Field West (slurry)	Tops weight	94	24436.0	18055.0
1) Field East (manure)	Tops nitrogen	18	2.4	3.7
1) Field East (manure)	Tops nitrogen	36	59.0	41.4
1) Field East (manure)	Tops nitrogen	64	139.2	180.4
1) Field East (manure)	Tops nitrogen	94	195.6	185.7
2) Field West (slurry)	Tops nitrogen	18	2.6	3.7
2) Field West (slurry)	Tops nitrogen	36	59.5	41.4
2) Field West (slurry)	Tops nitrogen	64	143.4	184.8
2) Field West (slurry)	Tops nitrogen	94	191.4	190.0

It is useful to make a graphical presentation of the agreement between measured and calculated values for crop models.

The most widespread graphical presentation can be obtained plotting, for each measurement, the measured value in the x axis and the corresponding calculated value in the y axis. It is also usual to draw the 1:1 line on the graphic. If there is no model error the calculated values and measured values are identical and then each point will be exactly on the 1:1 line. This type of graphic representation was made for the biomass produced and the plants N uptake during the maize crops growing seasons in 2007 and 2008. To compares model predictions and observed data the *root mean squared error* (RMSE) was calculated. It was 2799 Kg ha^{-1} for the biomass produced and 36.50 Kg ha^{-1} for the N uptake by the crops in the growth seasons 2007 and 2008.

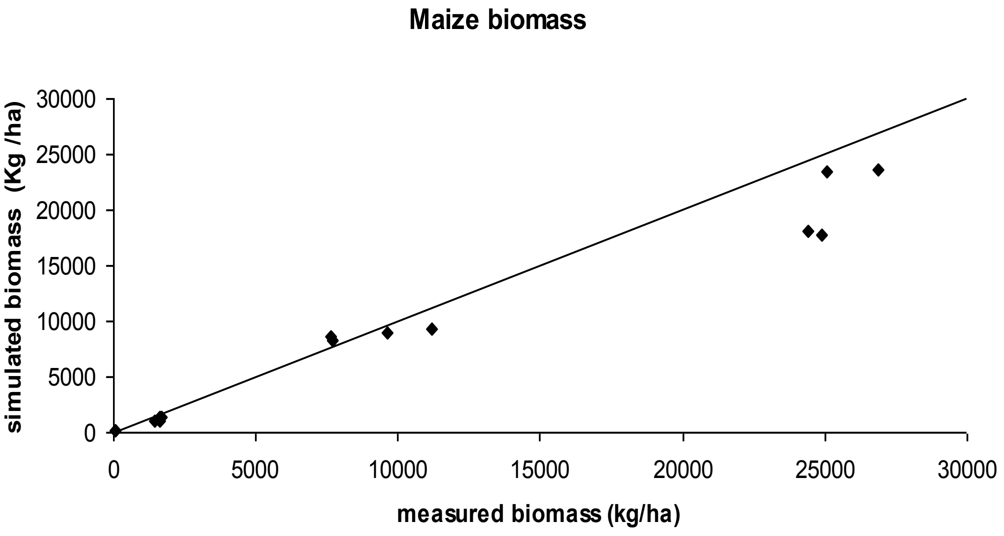


Figure 11. Measured and simulated maize biomass for 2007 – 2008, for the Arborea study site.

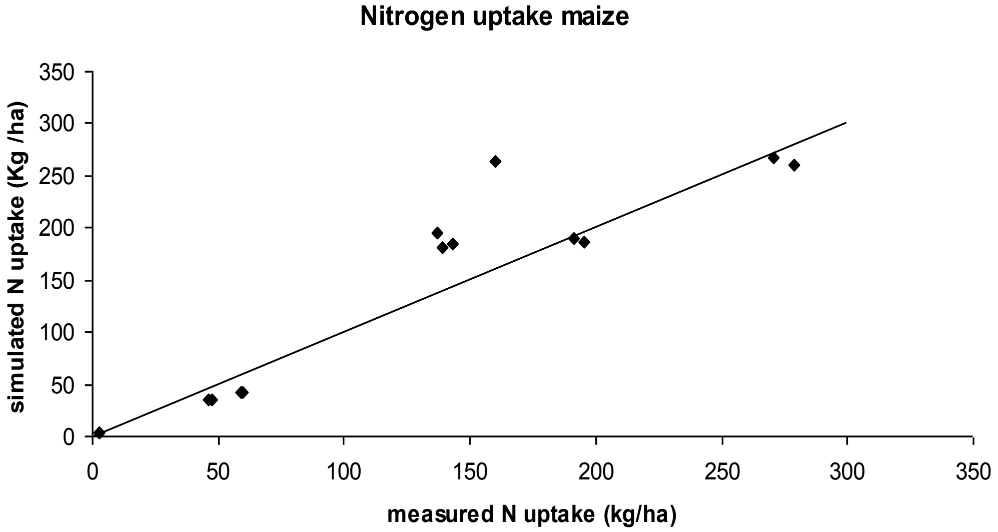


Figure 12. Measured and simulated maize nitrogen uptake for 2007 – 2008, for the Arborea study site.

4.3 Testing the DSSAT-CSM with the triticale crop.

In this part will be presented the DSSAT-CSM experiment file regarding the triticale crop (using wheat in DSSAT-CSM) in the experimental field in the NVZ of Arborea in the years 2007-2008.

Before the sowing of this crop, was distributed slurry in both side of the experimental field. The model has simulated well the anthesis date (observed: 128 days after planting; simulated: 128 days after planting).

The model overestimated the variable tops weight at harvest maturity: field east: observed vs. simulated: 7193 Kg ha^{-1} vs. 14009 Kg ha^{-1}; field west: observed vs. simulated: 6554 Kg ha^{-1} vs. 14126 Kg ha^{-1}. The variable tops N at harvest maturity has been overestimated for both parts of the experimental field (field east: observed vs. measured:101.2 Kg ha^{-1} vs. 143 Kg ha^{-1}; field west: 87.82 Kg ha^{-1} vs. 144 Kg ha^{-1}).

The difference between measured and simulated data was caused, probably to the fact that, during the season, the triticale crop was affected by a nematode pests attack. The model underestimated the total soil NO_3^- content, the only value overestimated by the model is the total soil NO_3^- content of the 220th day after the start of simulation in the east part of the experimental field. The output files of the DSSAT-CSM experiments concerning the triticale crop in the year 2007 and 2008 are summarized in tables 15 and 16.

Table 15. Observed and simulated total soil NO_3^- for the triticale crop in 2007-2008.

Treatments	Variable	Days after start of simulation	Measured Values (Kg ha^{-1})	Simulated values (Kg ha^{-1})
1) Field East	Total soil NO_3^-	100	1504.0	1023.8
1) Field East	Total soil NO_3^-	130	1474.0	918.4
1) Field East	Total soil NO_3^-	165	1769.0	1014.7
1) Field East	Total soil NO_3^-	220	924.7	1173.3
2) Field West	Total soil NO_3^-	100	1022.0	725.9
2) Field West	Total soil NO_3^-	130	1479.0	607.1
2) Field West	Total soil NO_3^-	165	1439.0	671.8
2) Field West	Total soil NO_3^-	220	1056.0	769.8

Table 16. Observed and simulated tops weight and tops N for the triticale crop in 2007-2008.

Treatments	Variable	Days after planting	Measured values (Kg ha^{-1})	Simulated values (Kg ha^{-1})
1) Field East	Tops weight	82	1349	2910
1) Field East	Topsweight	117	3201	5685
1) Field East	Topsweight	172	7193	14009
2) Field West	Topsweight	82	1075	2910
2) Field West	Tops weight	117	2916	5733
2) Field West	Tops weight	172	6554	14126
1) Field East	Topsnitrogen	82	47.4	112.6
1) Field East	Topsnitrogen	117	89.6	144.6
1) Field East	Topsnitrogen	172	101.2	142.5
2) Field West	Topsnitrogen	82	42.3	112.6
2) Field West	Tops nitrogen	117	75.9	145.5
2) Field West	Tops nitrogen	172	87.8	144.0

4.4 DSSAT-CSM Long term seasonal simulation scenarios results

The DSSAT-CSM long term (50 years) seasonal simulation scenarios results related to the maize crop are summarized in table 17 and in figures 13 and 14. Table 17 and figures 13 and 14 contains the fifty years average values, the standard errors and the confidence intervals of biomass production and irrigation amounts associated to the two treatments and to the different simulation scenarios considered.

Table 17. Fifty years average biomass values and standard errors, and irrigation amounts related to the two treatment (manure and slurry) and to the different simulation scenarios considered.

			MANURE TREATMENT; BIOMASS (t/ha)		
SCENARIOS	**N Conv.**	**N min.**	**N0**	**PUA 1**	**PUA 2**
CONV. IRR.	**22.68** ± 0.23	**22.04** ± 0.20	**21.98** ± 0.25	**22.05** ± 0.20	**22.26** ± 0.21
AUTO IRR.	**22.91** ± 0.24	**22.59** ± 0.23	**22.53** ± 0.22	**22.15** ± 0.26	**22.87** ± 0.24
MIN. IRR.	**21.04** ± 0.21	**20.11** ± 0.23	**19.69** ± 0.30	**20.02** ± 0.23	**20.28** ± 0.22

			SLURRY TREATMENT; BIOMASS (t/ha)		
SCENARIOS	**N Conv.**	**N min.**	**N0**	**PUA 1**	**PUA 2**
CONV. IRR.	**22.53** ± 0.27	**22.59** ± 0.22	**22.45** ± 0.23	**22.75** ± 0.23	**22.89** ± 0.24
AUTO IRR.	**22.91** ± 0.24	**22.60** ± 0.22	**22.53** ± 0.22	**22.90** ± 0.24	**22.91** ± 0.24
MIN. IRR.	**20.03** ± 0.31	**20.13** ± 0.23	**19.72** ± 0.30	**20.77** ± 0.21	**20.08** ± 0.29

			IRRIGATION AMOUNT (mm/ha)		
SCENARIOS	**N Conv.**	**N min.**	**N0**	**PUA 1**	**PUA 2**
CONV. IRR.	**603.0**	**603.0**	**603.0**	**603.0**	**603.0**
AUTO IRR.	**400.2**	**353.4**	**352.3**	**361.7**	**401.6**
MIN. IRR.	**380.0**	**380.0**	**380.0**	**380.0**	**380.0**

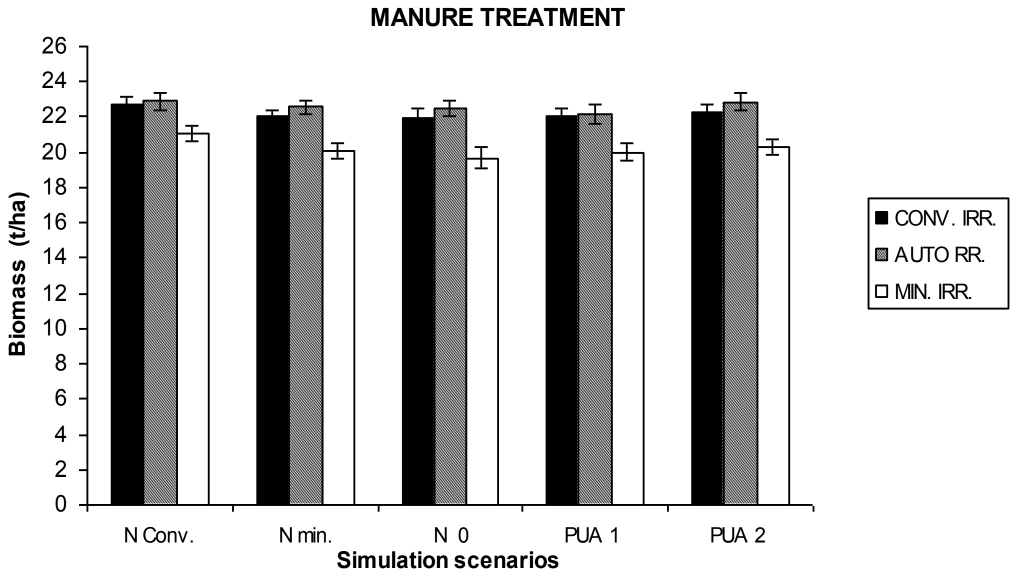


Figure 13. Fifty years average biomass and confidence intervals related to the manure treatment and to the different simulation scenarios considered.

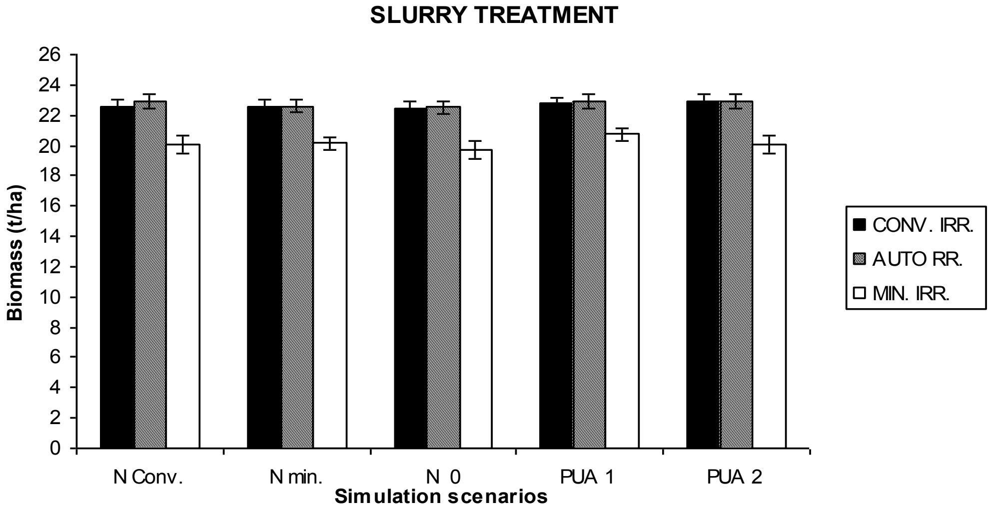


Figure 14. Fifty years average biomass and confidence intervals related to the slurry treatment and to the different simulation scenarios considered.

As reported in the table 17 and in the figures 13 and 14, the highest amount of biomass produced during the season for both treatment and for all the five N management strategies was reached using the automatic irrigation strategy, although the difference was not significant from the conventional irrigation scenario. The minimal irrigation scenario showed a difference of about 1.5 – 2 t ha^{-1} in the biomass production, for the two treatments, and for all the fertilization scenarios considered, compared to the conventional and automatic irrigation strategies.

The temporal variability of N leaching was assessed using the cumulative probability analysis (tables 18-23) relative to 50-year N leached averages values in the different scenarios. The percentiles values show that the N leaching is mainly affected by the irrigation management strategies. The nitrates leaching seems to be more responsive to the automatic irrigation strategy compared to the other two irrigation scenarios for both treatments and for the five different fertilizer management strategies considered.

Table 18. Statistics of N management strategies and leaching for the manure treatment and conventional irrigation strategy.

Statistics	Simulation Scenarios: N Leached (Kg ha^{-1})				
	N CONV.	N MIN.	N0	PUA 1	PUA 2
Average	910.90	865.32	793.70	844.21	817.18
Standard Deviation	173.92	151.00	113.13	121.62	124.95
Standard Error	24.60	21.36	16.00	17.20	17.67
Percentiles					
$P_{0.10}$	651.00	676.50	676.90	687.70	652.80
$P_{0.20}$	760.10	756.30	696.50	744.70	713.20
$P_{0.30}$	804.40	799.50	709.90	771.30	739.70
$P_{0.40}$	846.80	815.40	742.60	808.20	784.10
$P_{0.50}$	910.10	852.30	776.60	824.00	810.50
$P_{0.60}$	943.50	898.70	815.10	875.10	844.50
$P_{0.70}$	1011.30	936.80	844.20	901.10	872.80
$P_{0.80}$	1041.90	968.90	886.10	929.30	916.60
$P_{0.90}$	1029.10	1012.60	919.30	967.60	959.60
$P_{0.99}$	1324.00	1283.00	1146.70	1205.50	1163.40

Table 19. Statistics of N management strategies and leaching for the manure treatment and automatic irrigation strategy.

Statistics	Simulation Scenarios: N Leached (Kg ha^{-1})				
	N CONV.	N MIN.	N0	PUA 1	PUA 2
Average	115.93	94.87	93.12	103.94	104.84
Standard Deviation	135.31	114.93	103.73	103.31	99.58
Standard Error	19.14	16.25	14.67	14.61	14.08
Percentiles					
$P_{0.10}$	13.30	12.30	12.20	28.20	31.20
$P_{0.20}$	19.90	13.70	13.70	34.30	35.90
$P_{0.30}$	25.10	17.20	17.20	37.20	41.30
$P_{0.40}$	28.60	22.70	22.70	42.60	44.10
$P_{0.50}$	39.20	30.50	30.50	48.80	48.30
$P_{0.60}$	49.30	53.60	53.60	66.80	64.80
$P_{0.70}$	130.40	98.20	98.00	134.40	131.70
$P_{0.80}$	265.00	193.50	193.10	179.60	161.20
$P_{0.90}$	342.50	283.60	250.60	251.10	251.90
$P_{0.99}$	441.70	460.10	458.30	496.30	470.20

Table 20. Statistics of N management strategies and leaching for the manure treatment and minimal irrigation strategy.

Statistics	Simulation Scenarios: N Leached (Kg ha^{-1})				
	N CONV.	N MIN.	N0	PUA 1	PUA 2
Average	466.52	468.00	457.00	441.10	379.56
Standard Deviation	139.81	186.00	170.28	180.84	152.17
Standard Error	19.77	26.3	24.08	25.58	21.52
Percentiles					
$P_{0.10}$	318.40	273.50	270.90	256.00	243.50
$P_{0.20}$	344.40	307.30	308.60	288.60	253.80
$P_{0.30}$	356.00	363.50	358.50	336.10	275.60
$P_{0.40}$	389.10	385.30	380.80	358.30	297.60
$P_{0.50}$	433.70	396.30	394.20	366.80	303.20
$P_{0.60}$	469.90	425.10	420.40	386.60	336.10
$P_{0.70}$	514.80	447.50	445.10	429.80	439.20
$P_{0.80}$	574.30	677.40	654.80	629.60	480.10
$P_{0.90}$	641.20	787.60	722.20	770.30	629.20
$P_{0.99}$	855.10	916.50	844.40	865.70	815.70

Table 21. Statistics of N management strategies and leaching for the slurry treatment and conventional irrigation strategy.

Statistics	Simulation Scenarios: N Leached (Kg ha^{-1})				
	N CONV.	N MIN.	N0	PUA 1	PUA 2
Average	898.64	880.65	750.62	859.61	830.37
Standard Deviation	169.68	151.88	125.34	154.18	133.33
Standard Error	24.00	21.48	17.73	21.80	18.86
Percentiles					
$P_{0.10}$	704.90	683.60	601.30	633.10	668.90
$P_{0.20}$	721.90	769.50	643.60	730.90	725.80
$P_{0.30}$	769.60	788.50	673.60	780.60	751.80
$P_{0.40}$	815.00	829.50	689.80	807.00	773.40
$P_{0.50}$	865.40	856.90	724.80	865.00	801.30
$P_{0.60}$	917.56	896.60	762.10	896.20	851.70
$P_{0.70}$	1005.30	971.90	818.90	951.50	899.90
$P_{0.80}$	1066.10	998.70	865.70	983.30	947.60
$P_{0.90}$	1126.20	1032.90	894.60	1017.50	969.90
$P_{0.99}$	1303.70	1286.50	1112.10	1245.00	1210.20

Table 22. Statistics of N management strategies and leaching for the slurry treatment and automatic irrigation strategy.

Statistics	Simulation Scenarios: N Leached (Kg ha^{-1})				
	N CONV.	N MIN.	N0	PUA 1	PUA 2
Average	76.34	76.53	75.51	66.27	52.30
Standard Deviation	63.81	98.57	96.80	71.57	62.37
Standard Error	9.02	13.94	13.69	10.12	8.82
Percentiles					
$P_{0.10}$	23.90	9.70	9.70	17.20	10.30
$P_{0.20}$	32.00	10.80	10.80	20.96	15.60
$P_{0.30}$	40.80	13.50	13.50	26.23	19.00
$P_{0.40}$	48.90	16.20	16.20	29.80	26.40
$P_{0.50}$	61.20	24.10	24.10	33.56	30.10
$P_{0.60}$	76.60	38.50	38.50	50.29	42.40
$P_{0.70}$	90.20	76.00	75.90	64.39	51.40
$P_{0.80}$	107.10	136.30	135.90	94.75	71.50
$P_{0.90}$	134.40	257.40	245.40	178.60	115.90
$P_{0.99}$	415.90	414.60	412.80	374.21	314.40

Table 23. Statistics of N management strategies and leaching for the slurry treatment and minimal irrigation strategy.

Statistics	Simulation Scenarios: N Leached (Kg ha^{-1})				
	N CONV.	N MIN.	N0	PUA 1	PUA 2
Average	468.68	453.35	441.39	401.94	376.42
Standard Deviation	203.61	210.80	194.28	130.74	152.94
Standard Error	28.79	29.81	27.48	18.49	21.63
Percentiles					
$P_{0.10}$	252.10	236.60	236.60	264.40	234.00
$P_{0.20}$	298.50	279.20	277.70	300.80	251.10
$P_{0.30}$	312.60	335.60	351.50	327.70	280.00
$P_{0.40}$	359.90	358.30	352.10	333.20	304.40
$P_{0.50}$	398.00	373.70	368.70	357.40	327.40
$P_{0.60}$	475.60	400.60	394.90	378.40	370.20
$P_{0.70}$	547.50	428.30	416.40	440.50	430.90
$P_{0.80}$	665.00	690.70	666.90	503.20	491.60
$P_{0.90}$	713.70	816.90	773.80	605.30	766.50
$P_{0.99}$	940.70	966.30	893.70	790.60	956.10

Nitrogen leaching long term simulations results are reported in the table 24 and in figures 15 and 16. As clearly showed by the figures there were differences among the three irrigation strategies for both treatments and for the N fertilization scenarios considered.

Table 24. Fifty years average nitrogen leached values and standard errors, and irrigation amounts related to the two treatment (manure and slurry) and to the different simulation scenarios considered.

MANURE TREATMENT; N LEACHED (Kg/ha)					
SCENARIOS	**N Conv.**	**N min.**	**N 0**	**PUA 1**	**PUA 2**
CONV. IRR.	**910.9** ± 24.6	**865.3** ± 21.4	**793.7** ± 16.0	**844.2** ± 17.2	**817.2** ± 17.7
AUTO IRR.	**115.9** ± 19.1	**94.9** ± 16.3	**93.1** ± 14.7	**103.9** ± 14.6	**104.5** ± 14.1
MIN. IRR.	**466.5** ± 19.8	**467.0** ± 26.3	**457.0** ± 24.1	**441.1** ± 25.6	**379.6** ± 21.5

SLURRY TREATMENT; N LEACHED (Kg/ha)					
SCENARIOS	**N Conv.**	**N min.**	**N 0**	**PUA 1**	**PUA 2**
CONV. IRR.	**898.7** ± 24.0	**880.7** ± 21.5	**750.6** ± 17.7	**859.6** ± 21.8	**830.4** ± 18.9
AUTO IRR.	**76.3** ± 9.0	**76.5** ± 13.9	**75.5** ± 13.7	**66.3** ± 10.1	**52.3** ± 8.8
MIN. IRR.	**468.7** ± 28.8	**453.4** ± 29.8	**441.4** ± 27.5	**401.9** ± 18.5	**376.4** ± 21.6

IRRIGATION AMOUNT (mm/ha)					
SCENARIOS	**N Conv.**	**N min.**	**N 0**	**PUA 1**	**PUA 2**
CONV. IRR.	**606.0**	**606.0**	**606.0**	**606.0**	**606.0**
AUTO IRR.	**415.4**	**353.3**	**351.6**	**411.8**	**405.7**
MIN. IRR.	**380.0**	**380.0**	**380.0**	**380.0**	**380.0**

The N leached reaches very high values for both treatments and for all scenarios when the conventional irrigation strategy is used.

With the exception of the N0 fertilization strategy, the PUA 2 (170 Kg N ha^{-1} from organic fertilizer and 106 Kg N ha^{-1} from Urea) showed the lowest amount of N leached for both treatments.

In the manure treatment, the only difference was detected between the highest value, recorded in N CONV., and the lowest in N0.

In the slurry treatment, only the N0 fertilization strategy showed a lower N leaching compared to the other fertilization scenarios.

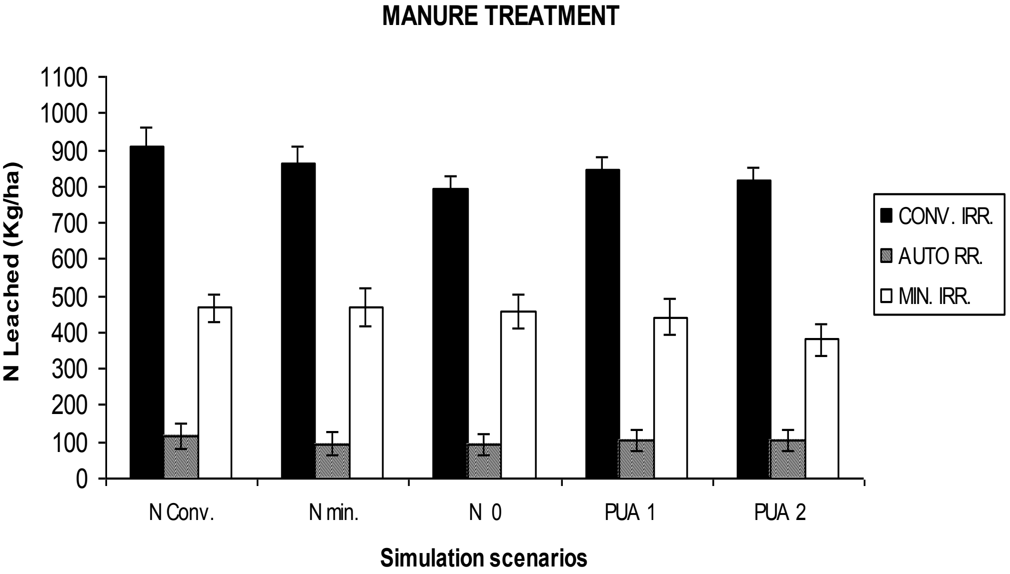


Figure 15. Fifty years average N leached and confidence intervals related to the manure treatment and to the different simulation scenarios considered.

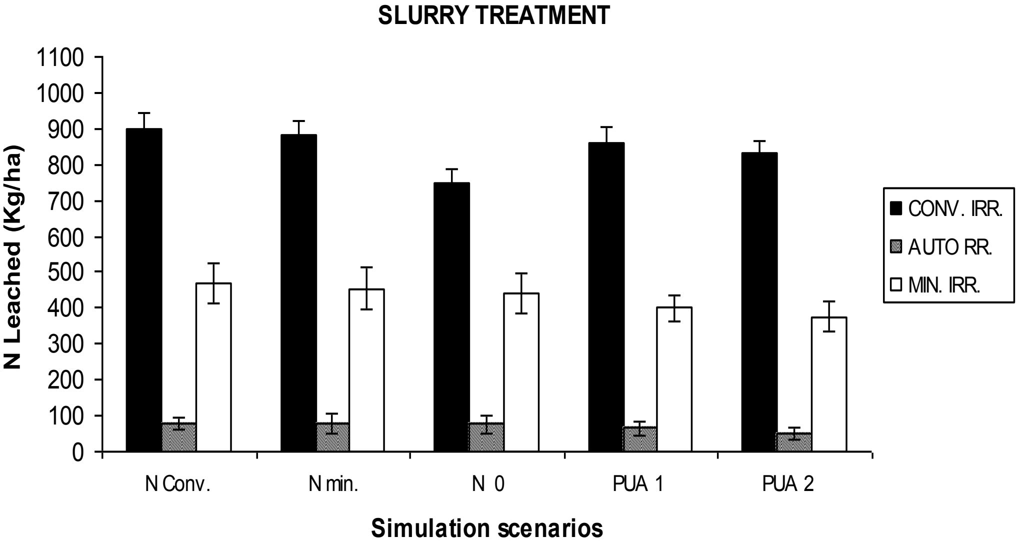


Figure 16. Fifty years average N leached and confidence intervals related to the slurry treatment and to the different simulation scenarios considered.

Considering the minimal irrigation strategy, a lower amount of N leached has been observed for both treatments and for all fertilization scenarios compared to the conventional irrigation. In this case, the PUA 2 showed the lowest amount of N leached in both treatments among all the fertilization strategies considered. In the manure treatment, only the N CONV. was different from the PUA 2 fertilization management, whereas no differences were observed among managements in the slurry treatment.

The best management irrigation strategy is the automatic. In fact, the amount of N leached simulated by the model was widely lower for both treatments and for all fertilization scenarios compared to the conventional and the minimal irrigation strategies.

The automatic irrigation strategy simulation results didn't show differences among the fertilizer management scenarios in both treatments.

The N leached by the PUA 2 of the slurry treatment was lesser than the N CONV, PUA 1 and PUA 2 of the manure treatment.

The results show that the amount of N leached (50 years average) for all the fertilization strategies was lower for the slurry treatment than for the manure treatment when automatic irrigation strategy is used.

The N0 and the PUA 2 fertilization strategies show the lowest amount of N leached, for the manure and the slurry treatment respectively. According to these results the best combination among the scenarios created with the DSSAT-CSM model is the PUA 2 of the slurry treatment using the automatic irrigation strategy.

This scenario maximize the biomass production and, at the same time, minimize the amount of N leached.

To better understanding the difference in the model results, the average fifty years seasonal simulation results of the following variables have been plotted using DSSAT-CSM: N mineralization, immobilization and net mineralization, N leaching and maize crop N uptake as function of the two treatments, automatic irrigation and the N management strategies.

The obtained results are summarized in tables 25 and 26 and in figures 17 and 18.

Table 25. Fifty years average values of N mineralization, immobilization, net mineralization, N leaching and N uptake as function of the manure treatment, automatic irrigation and the five N management strategies.

	MANURE TREATMENT				
	N MIN.	**N IMM.**	**NET MIN.**	**N LEACHED**	**N UPTAKE**
N CONV	1497.90	966.57	530.82	115.93	295.46
N 0	349.80	92.67	257.13	93.12	293.79
N MIN.	351.96	99.00	252.96	94.87	293.97
PUA 1	647.80	321.90	325.90	103.94	278.54
PUA 2	918.82	507.69	411.13	104.48	295.43

Table 26. Fifty years average values of N mineralization, immobilization, net mineralization, N leaching and N uptake as function of the slurry treatment, automatic irrigation and the five N management strategies.

	SLURRY TREATMENT				
	N MIN.	**N IMM.**	**NET MIN.**	**N LEACHED**	**N UPTAKE**
N CONV	2155.04	1602.26	552.79	76.34	295.38
N 0	319.84	87.57	232.27	75.51	293.83
N MIN.	321.54	92.80	228.74	76.53	293.95
PUA 1	976.78	626.40	350.38	70.77	295.42
PUA 2	1486.91	1036.84	450.07	52.30	295.44

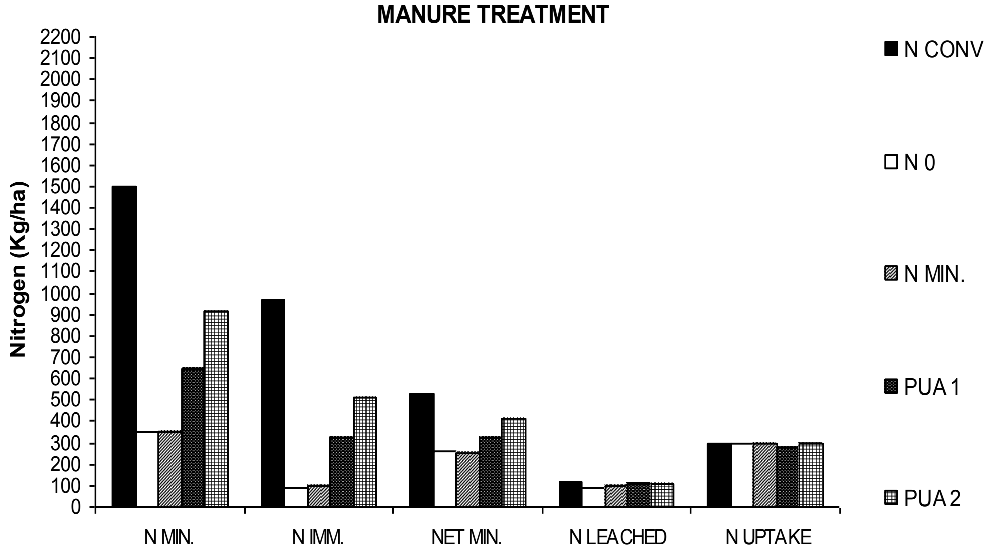


Figure 17. Fifty years average values of N mineralization, immobilization, net mineralization, N leaching and N uptake as function of the manure treatment, automatic irrigation and the five N management strategies.

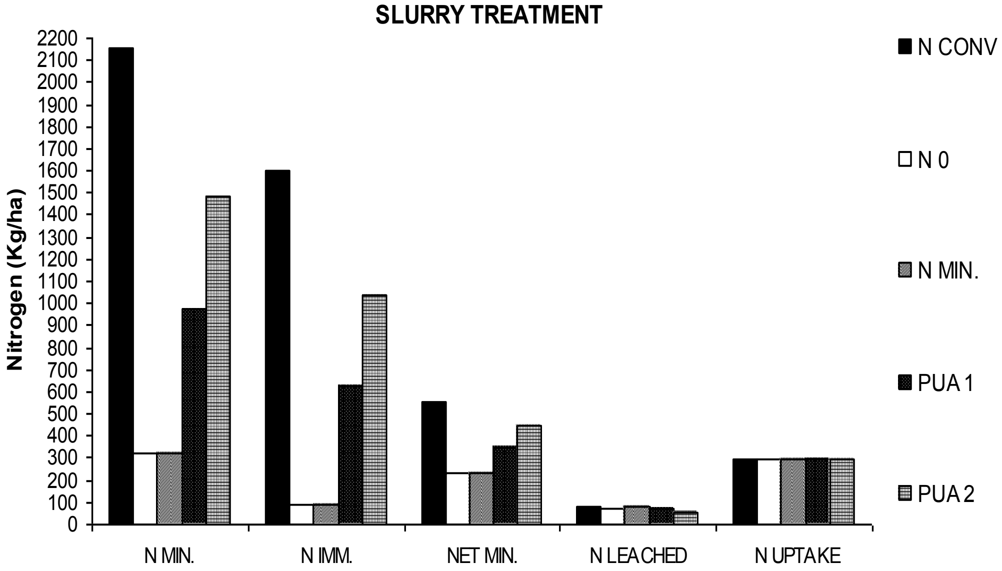


Figure 18. Fifty years average values of N mineralization, immobilization, net mineralization, N leaching and N uptake as function of the slurry treatment, automatic irrigation and the five N management strategies.

Based on the simulations results, between the two types of organic fertilizers considered, the use of slurry reduced the amount of N leached, because of the higher quantity of N immobilized during the maize crop growing season.

This difference is probably due to the lower N concentration of slurry (0.3%) in respect to manure (0.7%) and to the presumed higher C/N rate.

In addition, the simulations results suggest that the quantity of immobilized N increase with the amount of organic N fertilizers used.

4.5 SALUS rotational simulations results

4.5.1 2007-2008 rotational simulation results

The 2007-2008 rotational simulation results were compared with the measured values obtained from the samples collected in the experimental field. These comparisons are summarized in figures 19 and 20.

Figures 19 and 20 show observed and simulated values of the average total soil profile (from 0 to 1.40 m) nitrates content for the manure and slurry treatments for the twelve sampling dates made during the rotation, from June 2007 to September 2008.

The SALUS model simulated a lower amount of the average total soil profile nitrates compared to the measured values for all the sampling dates in both treatments. However, in most cases, simulated values matched the observed values. Some significant discrepancies were observed when the measured values were high (fig.19 – 20). The comparison between model predictions and observed data has been made by the RMSE calculation.

RMSE was calculated for two sets of comparisons.

The first RMSE was 497 Kg ha^{-1} and 474 Kg ha^{-1} for the manure and slurry treatment respectively, calculated including all the sampling data.

The second RMSE was 123 Kg ha^{-1} and 146 Kg ha^{-1} for the manure and slurry treatment respectively, calculated by eliminating unrealistic values probably due to the high spatial variability of the manure and slurry distribution and potential sampling error.

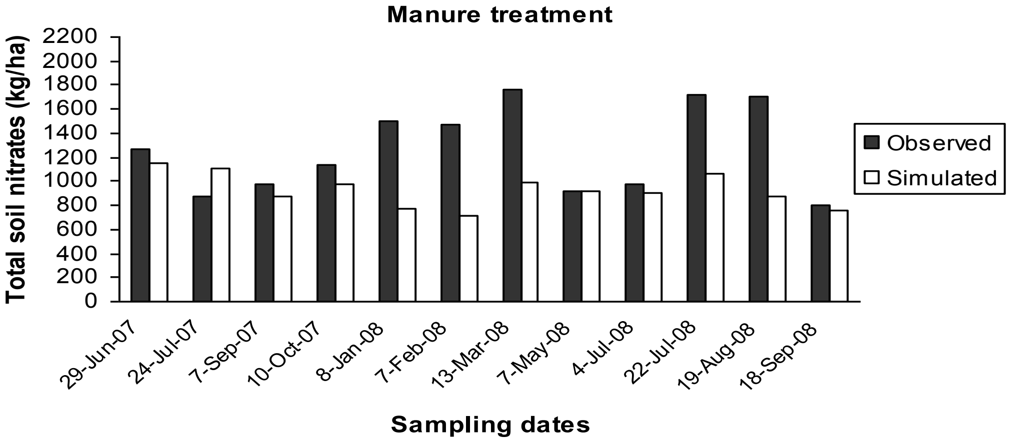


Figure 19. Observed and simulated values of total soil nitrates for the 2007 – 2008 rotation for the manure treatment.

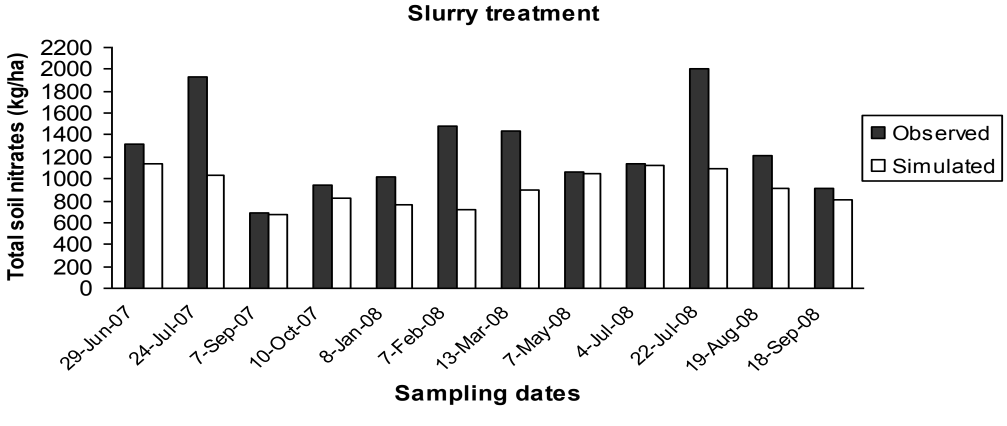


Figure 20. Observed and simulated values of total soil nitrates for the 2007 – 2008 rotation for the slurry treatment.

These results confirm the great variability in the soil nitrates content.

In the manure treatment the larger differences were found in five sampling dates, (January, February, March, July and August, 2008), whereas in the slurry treatment the larger differences were found in four sampling dates (July 2007, February, March and July 2008). In the other sampling dates, the differences were significantly smaller, and in some cases the observed and simulated values were practically the same. The minimum amount of total soil profile nitrates in manure was observed at the end of the rotation (September 2008) with the measured and simulated values of 796 Kg ha^{-1} and 755 Kg ha^{-1} respectively. The minimum amount of total soil profile nitrates in slurry was observed in on September 2007 (at the harvest date of the maize crop) with the measured and simulated values of 685 Kg ha^{-1} and 680 Kg ha^{-1} respectively.

At the end of the rotation, the slurry treatment contain the higher measured amount of soil nitrates compared to the manure treatment, although both treatments showed an extremely high level of soil nitrates, these results have been confirmed by the model simulations.

To better understanding the distribution of nitrate-N on the different soil profile layers during the rotation, the observed and simulated total soil nitrates content in eight layers related to eight sampling dates are reported in figures 21-38. These comparisons made possible to evaluate the variability of nitrates in the soil profile and the accuracy of model simulations.

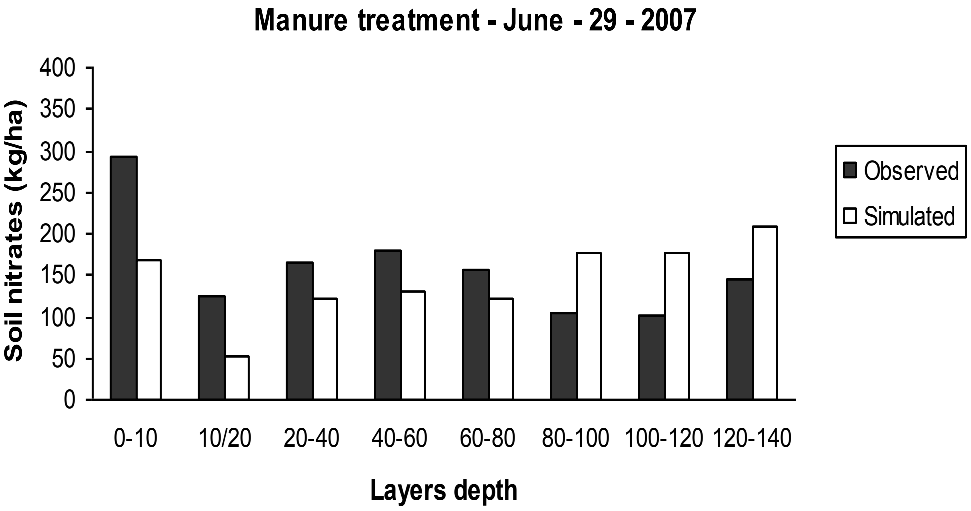


Figure 21. Observed and simulated soil nitrates in the different layers for the manure treatment on June-2007.

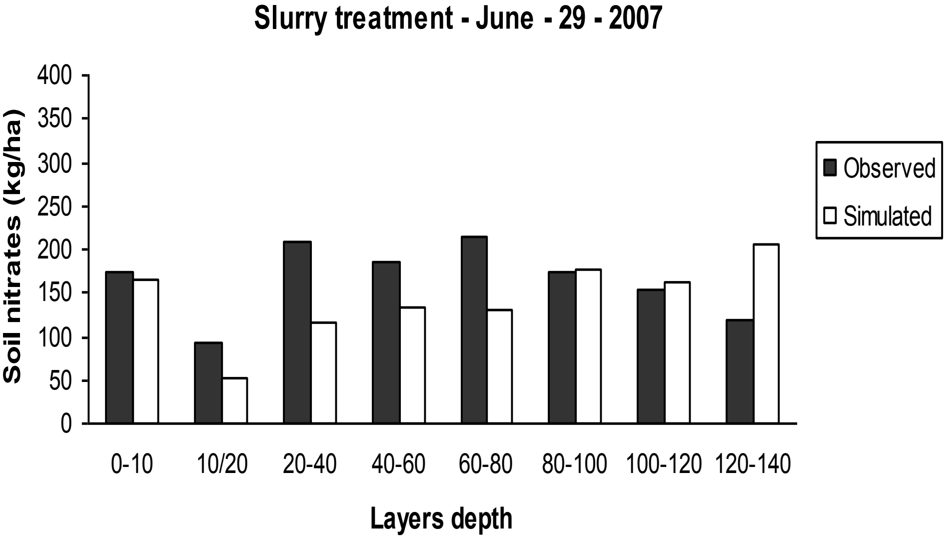


Figure 22. Observed and simulated soil nitrates in the different layers for the slurry treatment on June-2007

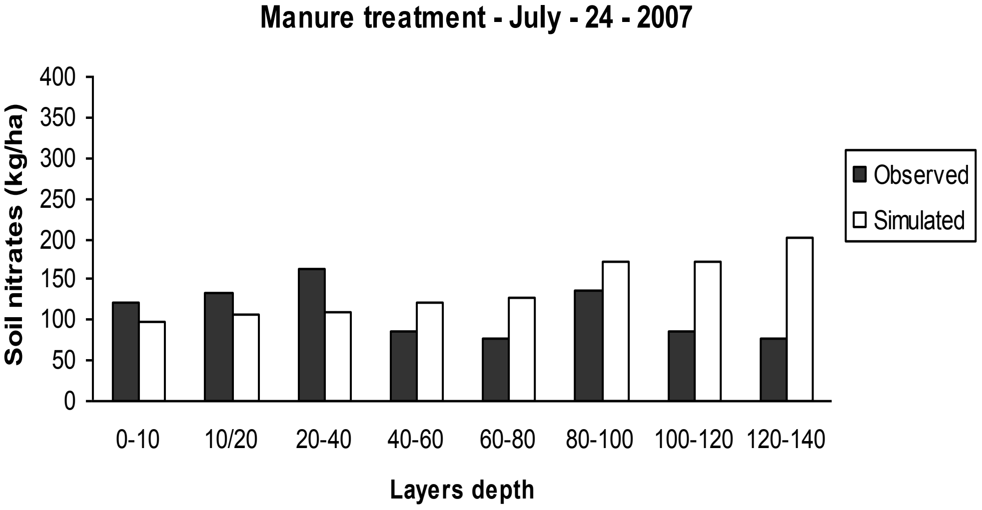


Figure 23. Observed and simulated soil nitrates in the different layers for the manure treatment on July-2007.

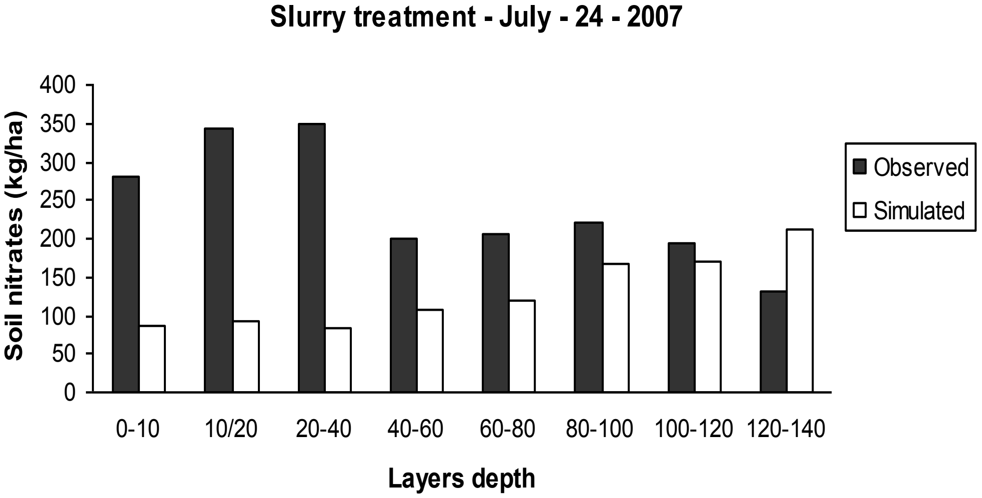


Figure 24. Observed and simulated soil nitrates in the different layers for the slurry treatment on July-2007.

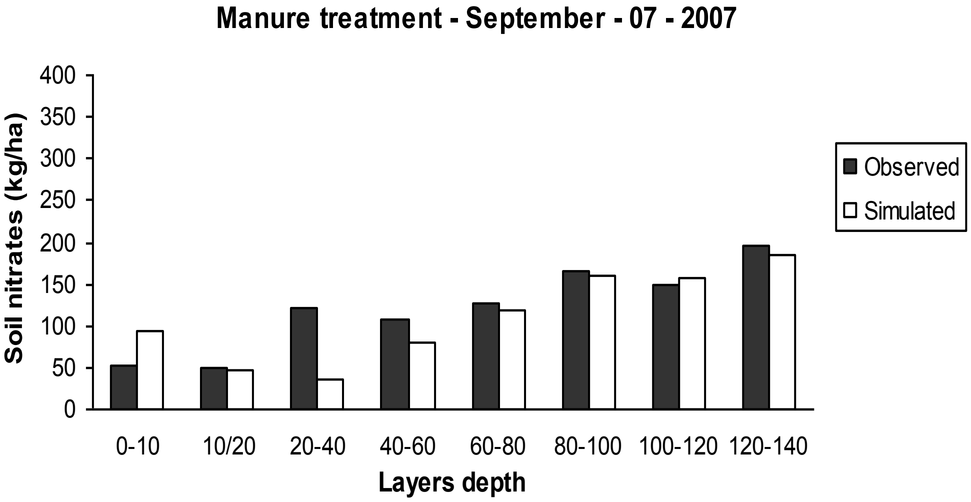


Figure 25. Observed and simulated soil nitrates in the different layers for the manure treatment on September-2007.

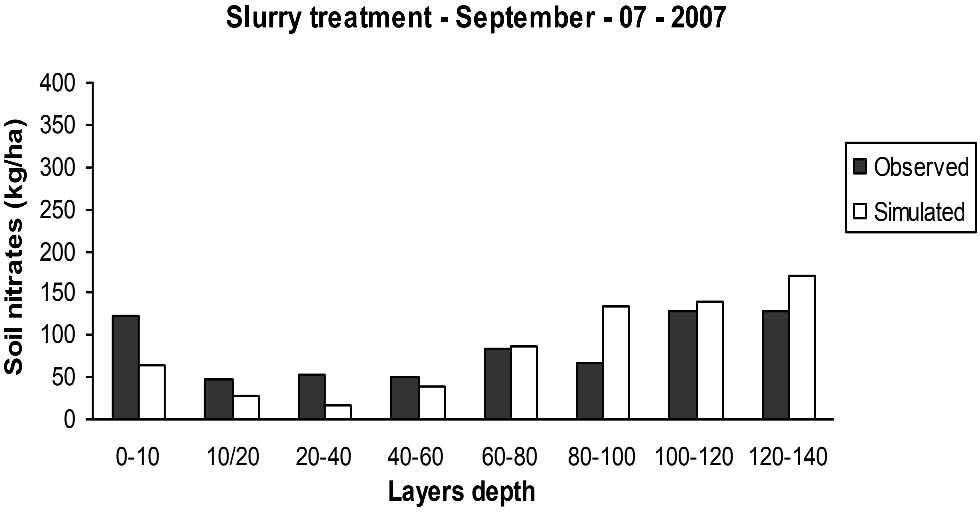


Figure 26. Observed and simulated soil nitrates in the different layers for the slurry treatment on September-2007.

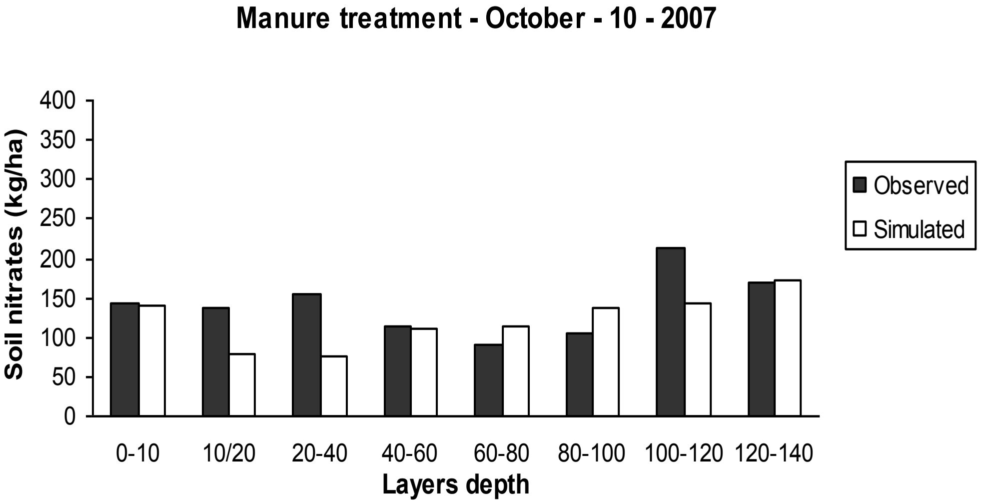


Figure 27. Observed and simulated soil nitrates in the different layers for the manure treatment on October-2007.

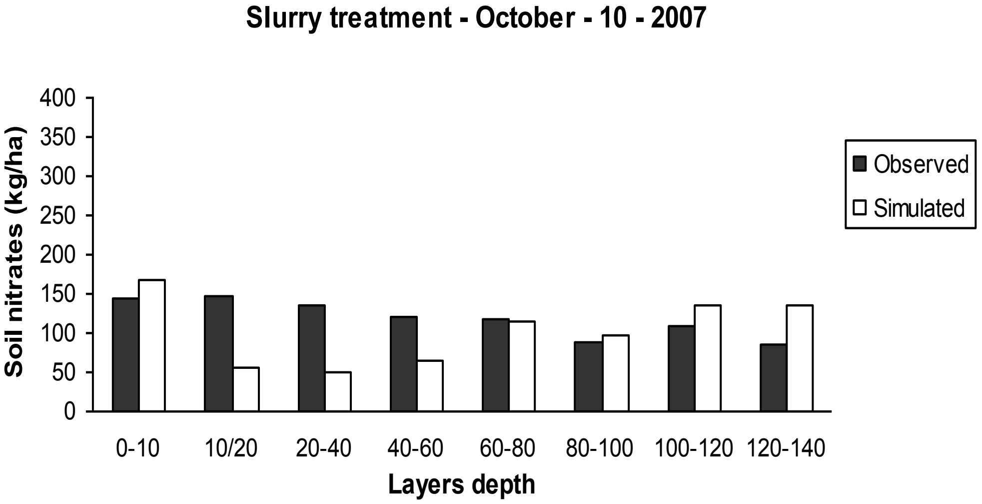


Figure 28. Observed and simulated soil nitrates in the different layers for the slurry treatment on October-2007.

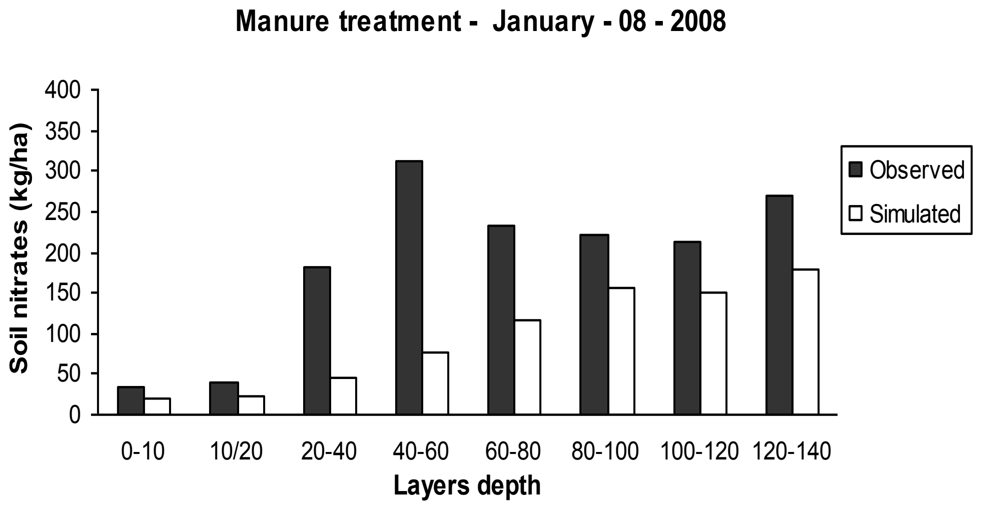


Figure 29. Observed and simulated soil nitrates in the different layers for the manure treatment on January-2008.

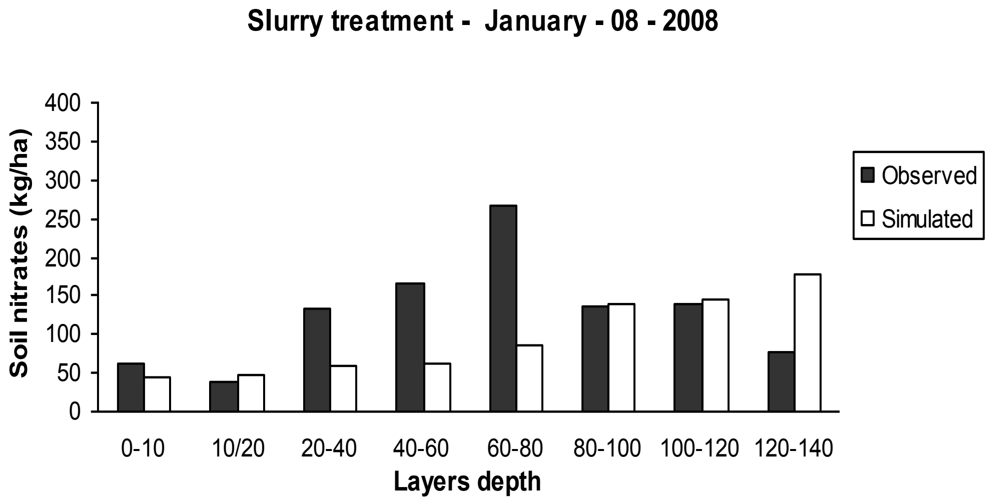


Figure 30. Observed and simulated soil nitrates in the different layers for the slurry treatment on January-2008.

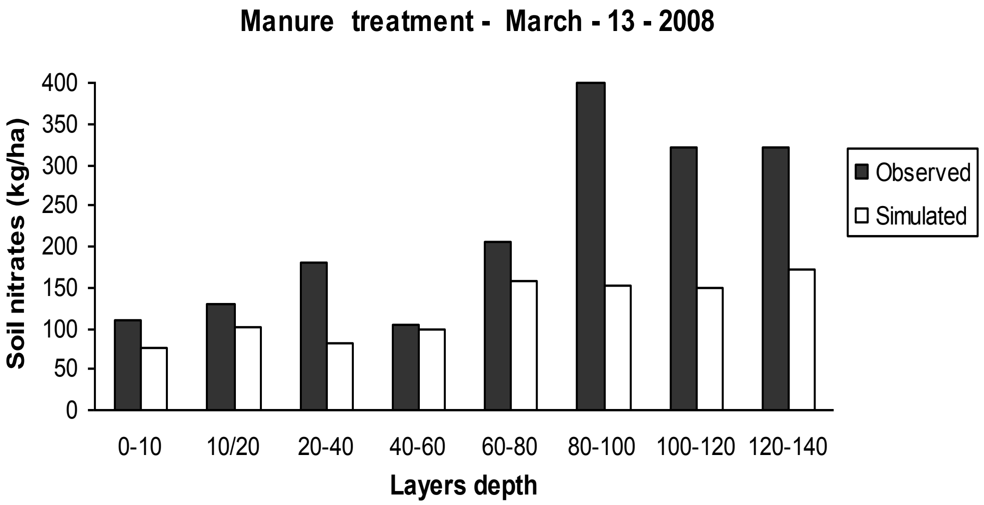


Figure 31. Observed and simulated soil nitrates in the different layers for the manure treatment on March-2008.

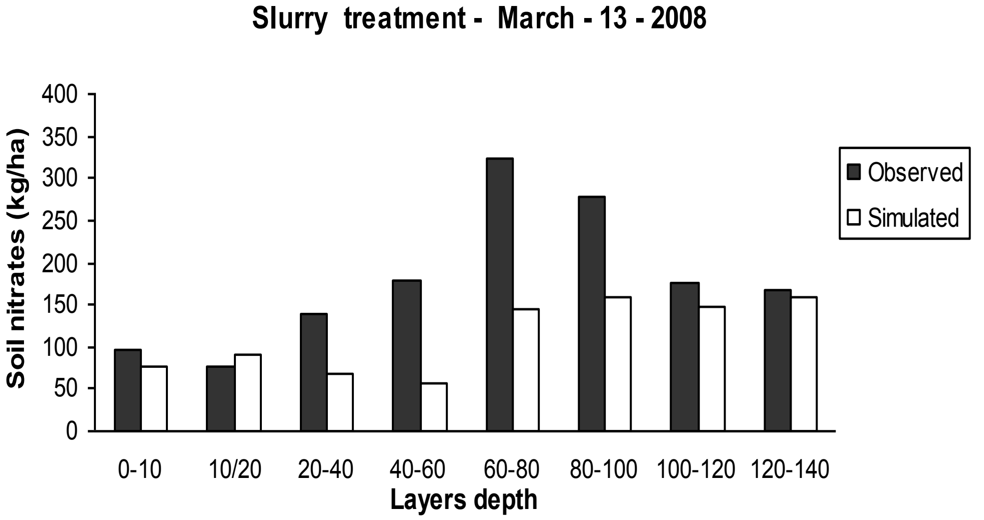


Figure 32. Observed and simulated soil nitrates, in the different layers for the slurry treatment on March-2008.

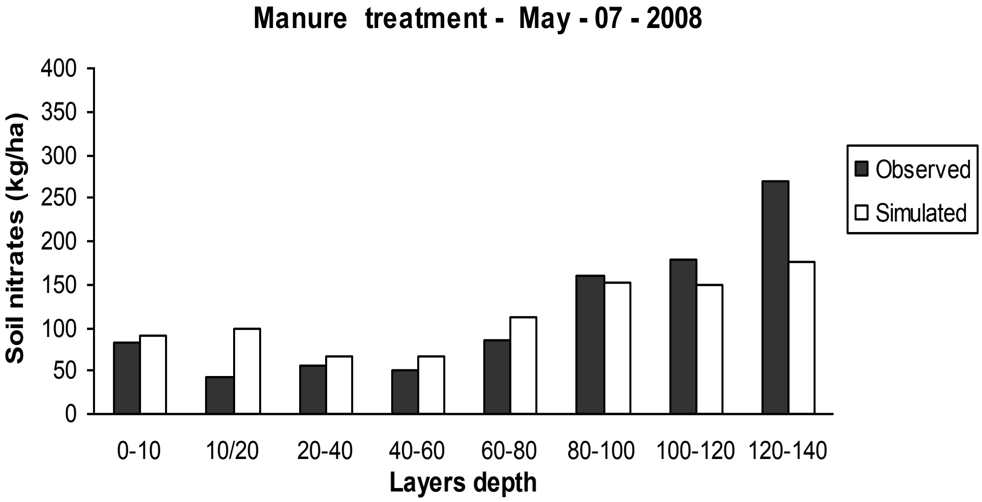


Figure 33. Observed and simulated soil nitrates, in the different layers for the manure treatment on May-2008.

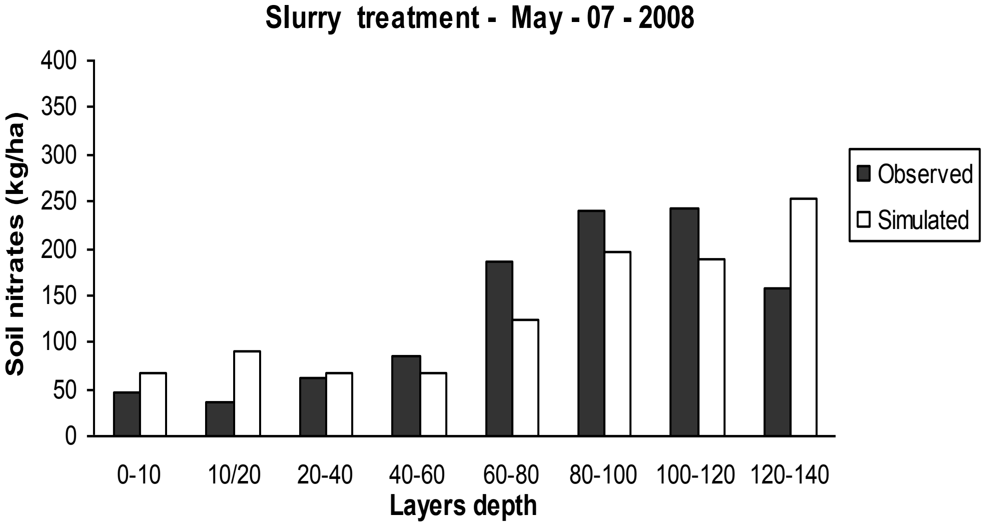


Figure 34. Observed and simulated soil nitrates, in the different layers for the slurry treatment on May-2008.

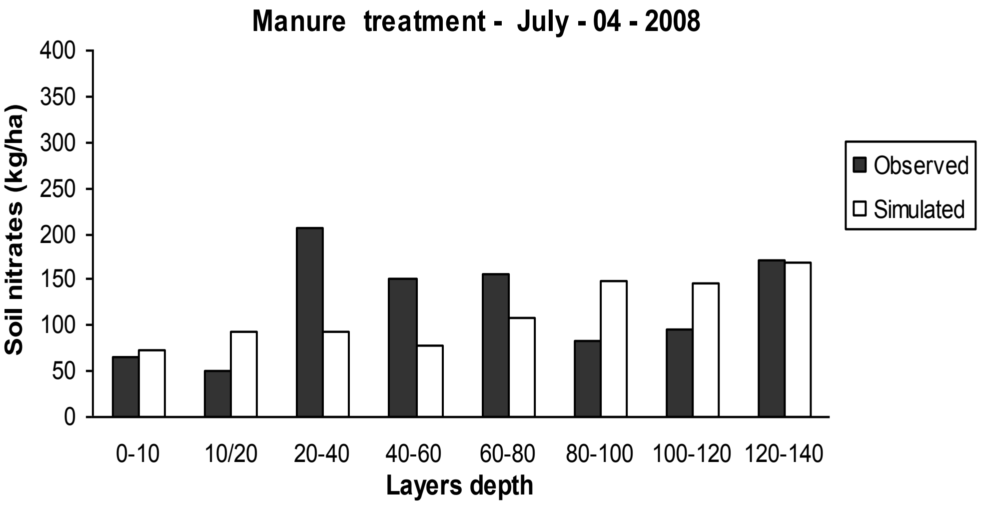


Figure 35. Observed and simulated soil nitrates, in the different layers for the manure treatment on July-2008.

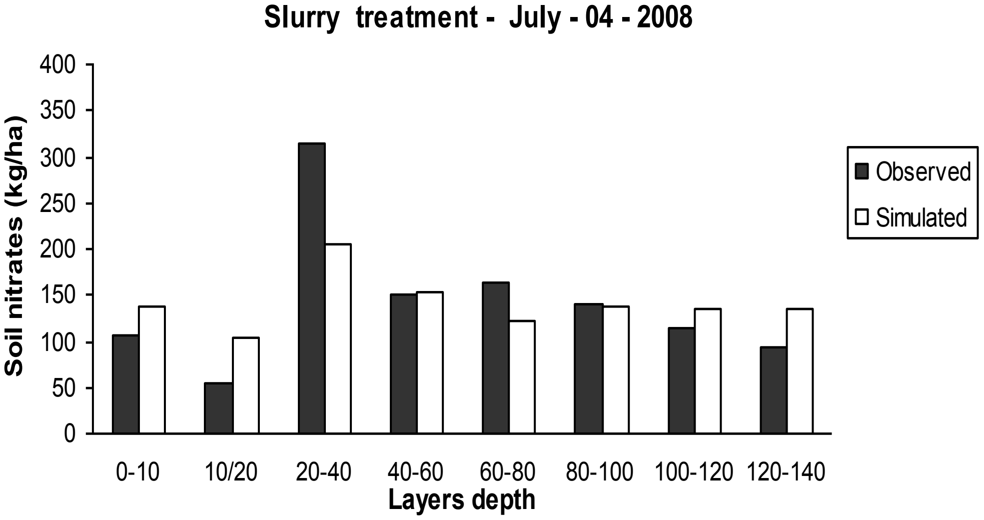


Figure 36. Observed and simulated soil nitrates, in the different layers for the slurry treatment on July-2008.

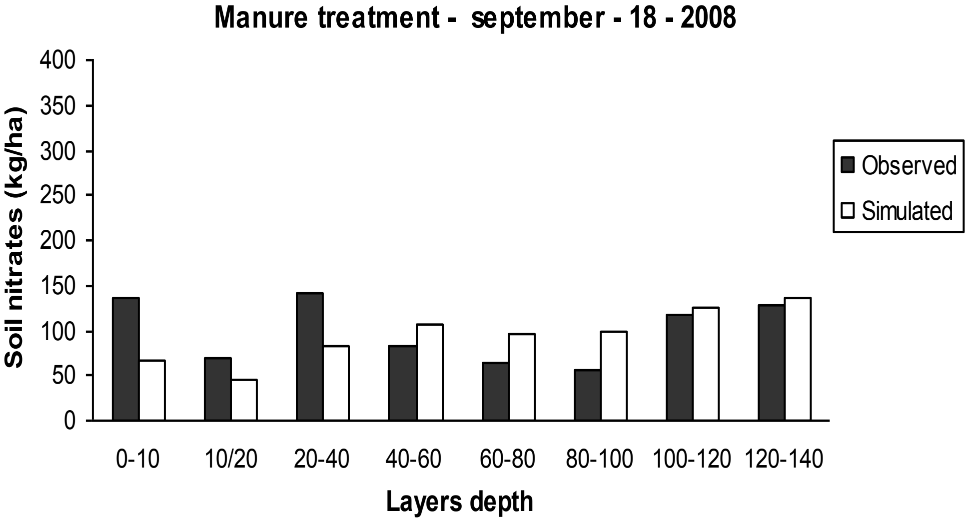


Figure 37. Observed and simulated soil nitrates, in the different layers for the manure treatment on September-2008.

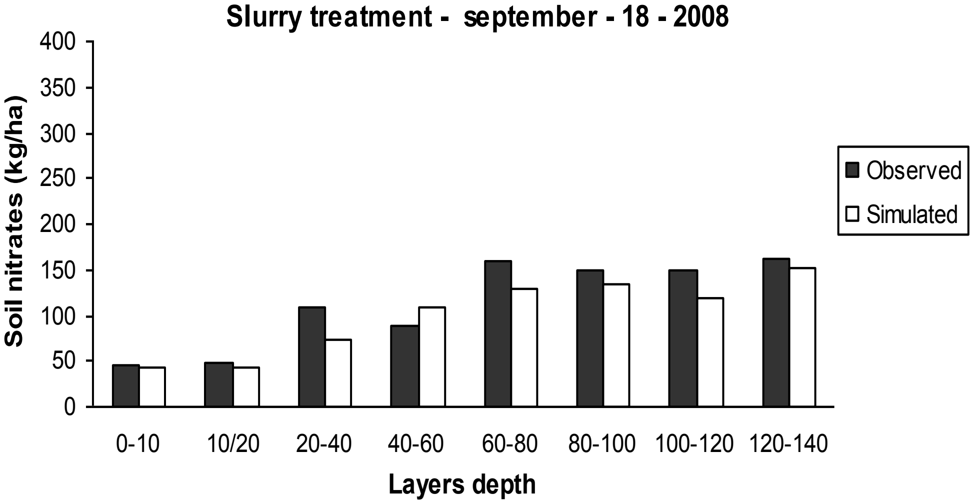


Figure 38. Observed and simulated soil nitrates, in the different layers for the slurry treatment on September-2008.

The SALUS model was able to provide satisfactory results when measured and simulated values of soil nitrates for each soil layers and sampling dates were compared (fig. 21-38). Although, as observed for the average total soil profile content (fig.19 and 20), some divergences were observed when the measured values were very high. The comparison between model predictions and observed data has been made by the RMSE calculation.

RMSE were calculated for each soil layers and sampling dates for the manure and slurry treatments (table 27).

Table 27. Root mean squared error for the variable soil nitrates for each soil layers and sampling dates for the manure and slurry treatments

Soil Layers (cm)	**Root mean squared error (RMSE)** **Manure ($Kg\ ha^{-1}$)**	 **Slurry ($Kg\ ha^{-1}$)**
0-10	**22.7**	**19.5**
10-20	**26.8**	**22.4**
20-40	**53.7**	**57.7**
40-60	**22.4**	**33.6**
60-80	**36.8**	**55.2**
80-100	**42.3**	**29.4**
100-120	**74.0**	**21.1**
120-140	**59.9**	**45.8**

The lowest RMSE for the manure treatment was observed for the 40 - 60 cm layer depth with the value of 22.4 Kg ha^{-1}, whereas the highest RMSE was observed for the 100 – 120 cm layer depth with the value of 74.0 Kg ha^{-1}.

The lowest RMSE for the slurry treatment was observed for the 0 -10 cm layer depth with the value of 19.5 Kg ha^{-1}, while the highest RMSE was observed for the 20 – 40 cm layer depth with the value of 57.7 Kg ha^{-1}.

4.5.2 Long term rotational simulation results

The first sets of long term (50 years) rotational simulation results assuming low N content, carried out to determine the effect of yearly application of manure and slurry in soil inorganic N and cumulative N leaching and to validate the SALUS model with the measured initial conditions of 2007 are reported in fig. 39 and 40.

The simulation results show that the inorganic soil N reaches a final value of 1228 Kg ha^{-1} and 1370 Kg ha^{-1} for the manure and slurry treatment respectively, when low soil inorganic N is used as initial condition.

The simulated values closely matched the measured soil inorganic N content at beginning of the experiment, on 06/29/2007; 1267 Kg ha^{-1} for the manure treatment and 1323 Kg ha^{-1} for the slurry treatment.

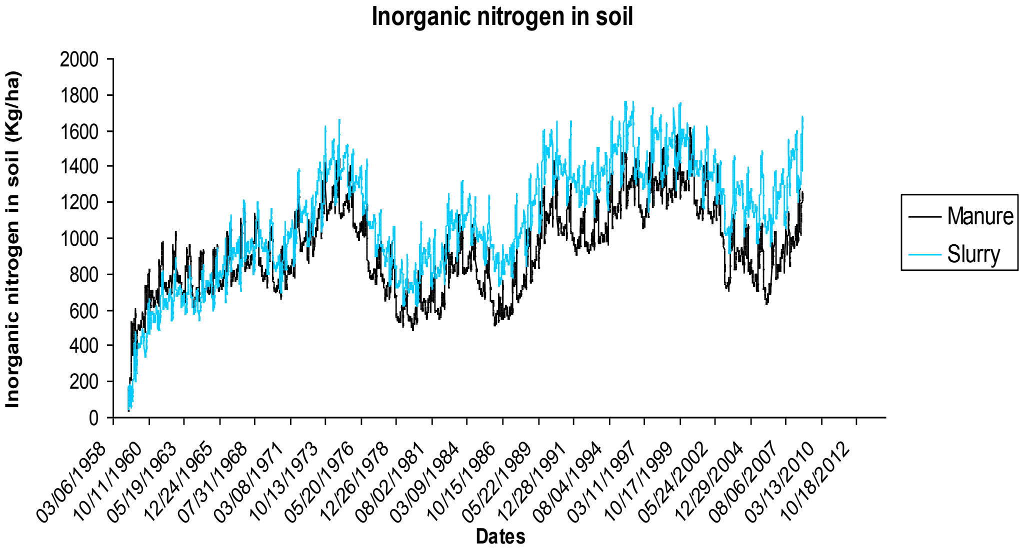


Figure 39. Simulated inorganic N in soil for the manure and slurry treatments in the long term rotation (1959-2008). Initial condition: low soil N content.

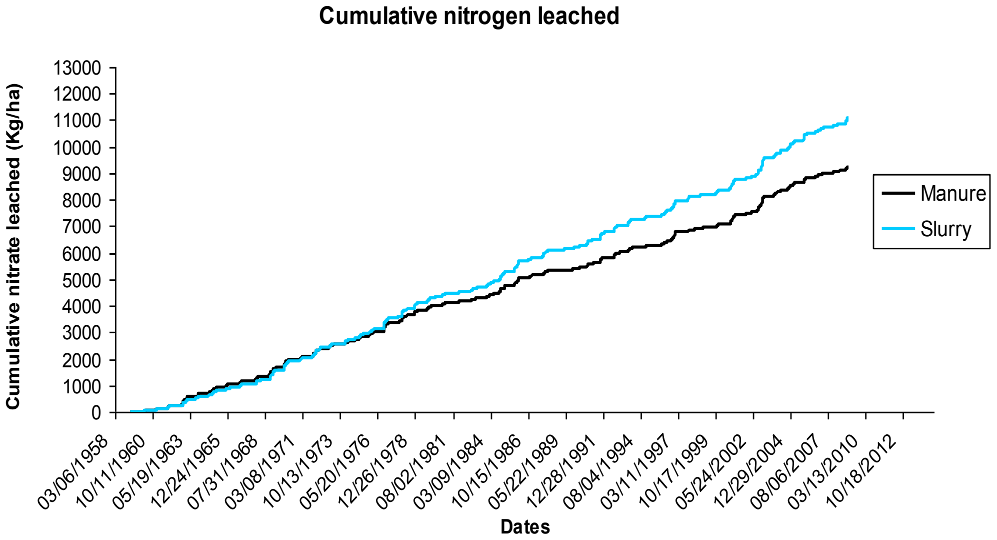


Figure 40. Simulated cumulative N leached for the manure and slurry treatments in the long term rotation (1959-2008). Initial condition: low soil N content.

Fig. 40 shows the simulated cumulative N leached in manure and in slurry treatments. The simulated cumulative amount of the nitrates leached was 9251 Kg ha^{-1} for the manure treatment and 11101 Kg ha^{-1} for the slurry treatment

The second sets of long term rotational simulation results using the initial conditions measured in 2007, carried out to evaluating the soil inorganic N content and the cumulative N leaching for manure and slurry applications for fifty years are reported in fig. 41 and 42.

The rotational simulation results show that the inorganic soil N reaches a final value of 1255 Kg ha^{-1} and 1677 Kg ha^{-1} for the manure and slurry treatment respectively.

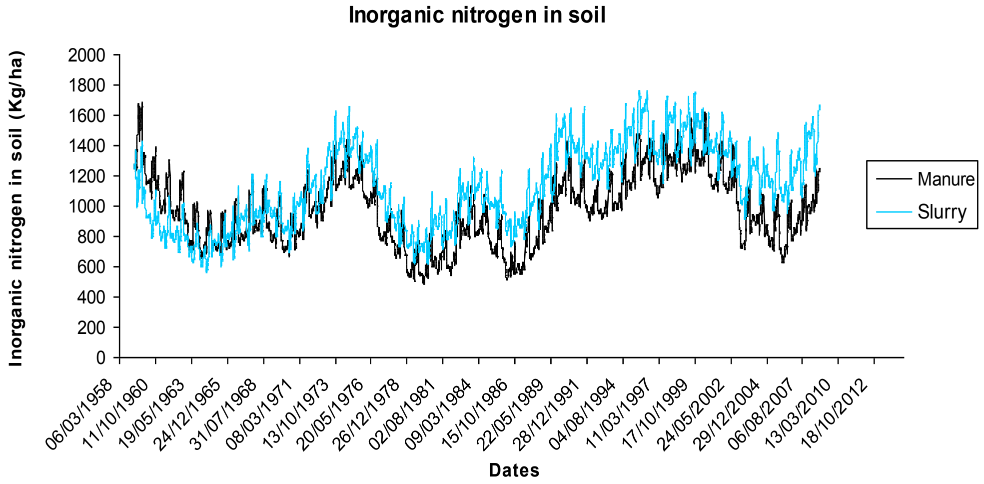


Figure 41. Simulated inorganic N in soil for the manure and slurry treatments in the long term rotation (1959-2008). Initial condition: soil N content measured in 2007.

Fig. 42 shows the simulated cumulative nitrate leached in manure and in slurry treatments. The simulated cumulative amount of the nitrates leached was 10373 Kg ha^{-1} for the manure treatment and 12088 Kg ha^{-1} for the slurry treatment.

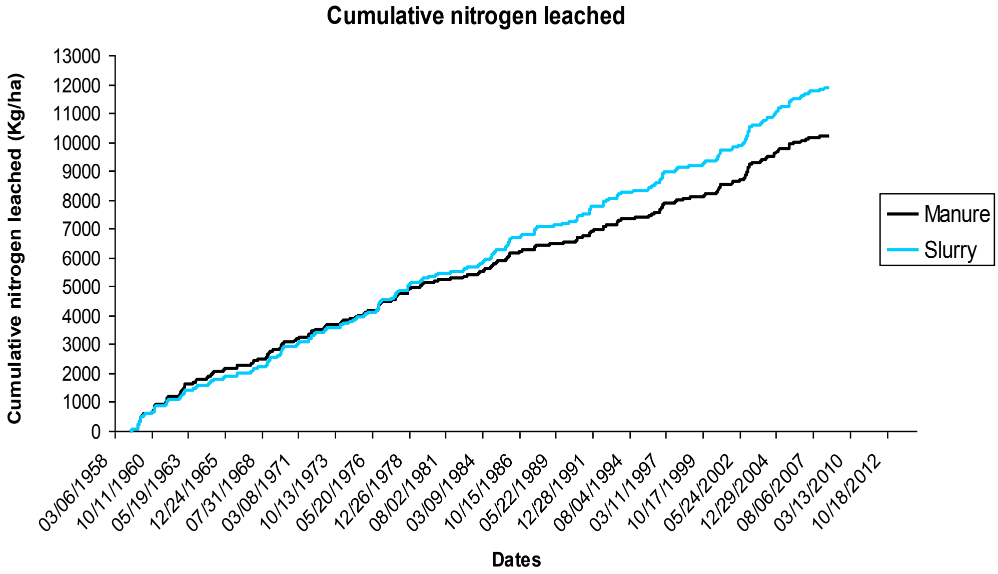


Figure 42. Simulated cumulative N leached for the manure and slurry treatments in the long term rotation (1959-2008). Initial condition: soil N content measured in 2007.

These results show that the nitrates leached rates were 242 Kg ha^{-1} year^{-1} for the slurry treatment and 207 Kg ha^{-1} year^{-1} for the manure treatment.

The SALUS model long term rotational results show that in the first seventeen years of simulations, from 1959 to 1976, the higher inorganic soil N and N leached amounts were observed in the manure treatment while from the end of 1976, the slurry treatment reached the higher values for both variables.

The third sets of long term rotational simulation results applying 276 Kg N ha^{-1} of urea as the only source of N (N MIN. fertilization strategy), carried out to compare its effect on leaching and inorganic soil N with the conventional management strategies are reported in table 28.

Table 28. Inorganic N in soil and cumulative N leached for the N CONV. and N MIN. fertilization strategies in the long term rotation (1959-2008).

Fertilization strategies	**Inorganic N in soil (Kg ha^{-1})**	**Cumulative N leached (Kg ha^{-1})**
N CONV. (organic N + urea)	**1400**	**12000**
N MIN. (276 Kg/ha of urea)	**223**	**4680**

The simulation results show that the inorganic soil N and the cumulative nitrate leaching reach a considerably higher value, when the conventional fertilization strategy is used.

5. CONCLUSIONS

The combination between the measured data- set and the use of DSSAT and SALUS models made possible to achieve the main objectives of this research.

The simulation results emphasize the environmental impact of inappropriate agronomic management strategies. These practices, even when the initial soil N content is low, could allow to reach extremely high values of soil N content and cumulative N leaching.

The simulations results also show that using irrigation volumes and scheduling based on the plant extractable soil water is possible to maintain an adequate biomass production and, at the same time, reducing significantly the amount of N leached into the soil profile.

Moreover, using a correct fertilization management strategy based on crops uptake is possible to decrease significantly the amount of N leaching, even when organic fertilizers are used.

These results underline that crop simulation models can support the selection of agronomic management options that allow to reduce the environmental pollution and the use of improper amount of management inputs and consequently to achieve an ecological improvement for the ecosystem and an economical return.

The manure and slurry samples analysis results show an higher N content and a presumed lower C/N rate in the manure compared to slurry.

The DSSAT-CSM long term seasonal simulation results show that the higher amount of N leached during the maize crop growing season was recorded in the manure treatment, the SALUS model long term rotational simulations results show the same result for the first 17 years of simulation whereas, from 1976 to the end of simulations (2008), the slurry treatment shows the higher amount of N leached. An hypothesis based on these results is that, both manure and slurry increase the soil organic matter although , due to the composition of the two organic fertilizers, the manure is able to increase the soil organic matter content in a greater rate compared to the slurry, and after 15-20 years (time required to observe a rise in the soil organic matter amount) could, potentially, immobilize an higher amount of N.

These hypothesis, outcome by model simulations, need to be confirmed by experimental data thus, in the future, a research based on this topic will be carry forward.

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