UNIVERSITY OF UDINE

Research doctorate in Agro-Environmental Sciences
Cycle XXVIII
Coordinator: Prof. Maria De Nobili

DISSERTATION

The assessment of nitrogen emissions from manure management and their mitigation adopting Short Rotation Coppice Crops

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ACADEMIC YEAR 2014/2015

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Abstract

Excess of reactive nitrogen is a matter of great concern, especially in developed countries. Reactive nitrogen can be dangerous to human health, for the environment (eutrophication, acidification of soils, emissions) and also for agriculture, because of the economic burden related with the disposal of manure, in the past a valuable nutrient, nowadays considered only a problem. Agriculture is responsible for a significant portion of nitrogen emissions. Livestock production, concentrated in some European regions, is the major contributor for ammonia emission, accounting almost 60% of the total, with losses of reactive nitrogen that occur along the whole manure management chain, from animal houses to storages of slurry and finally the spreading on agricultural land. With the increasing concern about the impacts of livestock production on natural resources and public health, international regulations have gone into effect with the objective of mitigating nitrogen emissions (N_2O and NH_3) to the atmosphere. Italy, in particular the North of the Country, presents a great development of animal husbandry and most of the agricultural land in Po Valley is considered a Nitrate Vulnerable Zone (NVZ) according to Nitrates Directive 91/676/EEC. However most of the studies on ammonia and nitrous oxide emission from slurry and related mitigation strategies come from north countries of Europe. For this reason, it is a priority to adjust emission assessments to the particular Mediterranean conditions, and finding mitigation strategies to limit nitrogen losses in these environments. Therefore, the current Ph.D. thesis was proposed with the aim of giving a contribute in the field of research on nitrogen assessment, with a special regard to emissions of ammonia from slurry management in innovative agricultural systems, such as Short Rotation Coppice Crops. Given the complexity of the issue this thesis has been organized in chapters,

that aim at presenting every aspect analyzed during three years of PhD and give an homogeneous framework of this work. In general, the following chapters have these outcomes (general conclusions):

Chapter 1: it synthetizes the state of the art on nitrogen losses from slurry chain, that is basically the sum of ammonia emission from storages and nitrogen losses (via leaching, emission and denitrification) from the application of slurry on agricultural land. Mitigation strategies (covers, short rotation coppice crops, distribution techniques) are presented, and measurement theories and techniques are introduced.

Chapter 2: a new model to simulate ammonia emission from slurry storages is introduced. The emission from slurry storages can vary largely depending on climate regime and management techniques, that include the type of storage and the adoption of mitigation strategies.

Chapter 3: a nitrogen balance, collecting data from field experiments on leaching, emission and nitrogen content of biomass has been done. Forested infiltration areas, where short rotation crops have been established, showed a good performance in the mature stage, whereas in the initial stage of the plantation the advantages were not relevant in comparison with traditional agricultural systems (Permanent meadow, Maize)

Chapter 4: a new model that simulates the growth of poplar and willow plantation has been developed. The yield of biomass crops can vary largely depending on soil characteristics and climate. The main results of this work consists in the vast ensemble of environmental and biological processes that this model can simulate. The relationship that links ageing of a plantation to biomass yield could be considered theoretical ad-

vancement for this category of crop models. To limit the problems that come from excess of reactive nitrogen in the environment, a set of solutions has been proposed in this thesis. These measures should be implemented all together accompanied with precise estimations of the ammonia emissions, on which still there is a great uncertainty.

Preface

Condensate in an homogenous work three years of work is a difficult task, especially for me, that I have been involved in a vast field of research on the nitrogen losses along the slurry management chain, and the associated abatement strategies. Indeed, my PhD experience has included diverse approaches: experimental campaigns on field, investigations using environmental models, and a marginal laboratory work, that was necessary in the first year of doctorate to develop a methodology to measure ammonia emission. Experimental campaigns were performed in Redafi and Florobasco projects, two projects financed by Veneto Agricoltura with the aim of investigating the nitrogen balance in forested rural ecosystems. A modelling approach was suitable to study such short rotation coppice systems, a new mechanist model named ESRC has been developed to study the growth of poplar and willow under different conditions of soil and climate and submitted to different agricultural practices. During the PhD I have spent three months in Denmark, working on a model to simulate ammonia emission from slurry storages, that is the first chapter of this thesis. This is considered a strategy for facing nitrogen challenge using phytoremediation, a cost effective plant-based approach. Despite the importance of these studies, still little is known about the nutrient use and efficiency of poplar SRCs, and how the amounts of trapped nitrogen can vary according to factors such as site conditions (Paris, 2014).Summing up, the focus of this thesis has been the investigation on ammonia and nitrogen oxide losses and abatement strategies along the slurry management chain, with the aim of giving a contribute in the challenge to reduce the loss of reactive nitrogen in the environment. Hence, to expand the knowledge on this topic, especially concerning ammonia emission in Italy. My works have been developed with the contribution of scientists in Systems Dynamics and the support of a research group with a solid experience in manure management, especially regarding the biogas sector. As a logical consequence of the interdisciplinary approach, I have decided to divide the proposed theses in chapters, each concerning an aspect studied during my work. A state of the art of the problems and opportunities related with manure management are introduced in the first chapter, that describe the link among the diverse topics. The objectives of this work can be synthetized as:

1) Identify measures to abate nitrogen losses along the slurry management chain, from the storage of slurry to the spreading on agricultural land

2) Investigate the process of ammonia volatilization in agro-ecosystems, with regard to Short Rotation Coppice in marginal areas, studying influencing parameters

3) Investigate the process of ammonia volatilization in storages, studying influencing parameters

The approaches that were adopted to get these points are:

1) A modelling approach to study the yields of bioenergy in response to environment and management practices, and another model dedicated to ammonia volatilization from storages.

2) Field experiments to monitor gaseous emission from slurry spreading and collecting data with other units of research, performing a nitrogen balance, doing a comparison between a permanent meadow and a short rotation system.

In general, the following chapters have these outcomes:

Chapter 1: it synthetizes the state of the art on nitrogen losses from slurry chain, that is basically the sum of ammonia emission from storages and nitrogen losses (via leaching, emission and denitrification) from the application of slurry on agricultural land. Abatement strategies (covers, short rotation coppice, distribution techniques) are presented, and measurement theories and techniques are introduced.

Chapter 2: a new model is introduced. The emission from slurry storages can vary largely depending on climate regime and management techniques, that include the type of storage and the adoption of abatement strategies.

Chapter 3: a nitrogen balance, collecting data from field experiments on leaching, emission and nitrogen content of biomass has been done. Forested infiltration area where short rotation has been established has a good performance in the mature stage, whereas in the initial stage of the plantation the advantages are not relevant in comparison with traditional agricultural systems

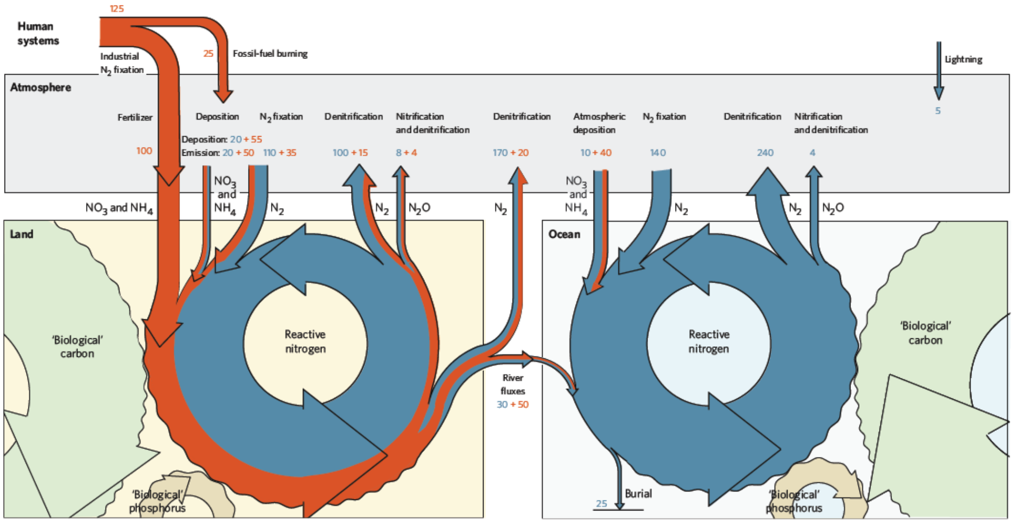
Chapter 4: a new model has been developed. The yield of biomass crops can vary largely depending on soil characteristics. The main results of this work consists in the vast ensemble of environmental and biological processes that this model can simulate. The relationship that links ageing of a plantation to biomass yield could be considered theoretical advancement for this category of crop models. The work of this thesis has placed the basis to improve environmental modules within the ESRC model.

1. State of the art

1.1 Nitrogen losses in the environment: ecological issues

The implications of the industrial transformation of agriculture are beyond agriculture matters. As stated by American scientist C.C. Delwiche in 1970 "The ingenuity that has been used to feed a growing world population will have to be matched quickly by an effort to keep the nitrogen cycle in reasonable balance". The Malthus warning about the growing of human population has been not confirmed, but the Earth has been paying an high price in term of sustainability. Not only for the pressure on the environment exercised by a growing population, but for significant changes in industrialization and consumers habits. In an article on Nature Journal (2008), Gruber and Galloway have underlined the importance of anthropogenic influences on the global nitrogen cycle, that is interconnected with other crucial geo-biochemical cycles, most notably those of phosphorus, sulphur and carbon (Falkowski *et al.*, 2000). Can management of the global nitrogen cycle help to mitigate climate change? This is one of the most vexed questions that regard sustainability in the Anthropocene, so named the era in the Earth history in which the anthropogenic influences on climate, ecological cycles and other living beings are considered crucial (Crutzen and Steffen, 2003). Reactive nitrogen is produced by a number of diverse sources, among these manure management has a great role (EPA, 2012). Nitrogen balance is an indicator of sustainability for agriculture: 'Gross nitrogen balance' estimates the potential surplus of nitrogen on agricultural land. This is done by calculating the balance between nitrogen added to an agricultural system (nitrogen input can be taken as a proxy indicator for the general intensity of agricultural management) and nitrogen removed from the system per hectare of agricultural land. The indicator accounts for all inputs to and outputs from the farm, and therefore includes nitrogen input. For a farm to be sustainable, the fertilization should be regulated considering the nitrogen content in soil, and the amounts of manure and fertilizers that are used to increase crop yields (Valkama *et al.*, 2012). The importance of the nitrogen balance approach has been for long misunderstood, but since the 80's, due to the so called "nitrogen bomb", that leads to vast environmental negative consequences, it has been proved that the fate of the nitrogen is a great environmental concern. Like in other balances, the optimum is reached when there is an equilibrium among sink and sources, that is not the case of contemporary intensive agricultural systems, especially in developed and industrialized countries (Sutton, 2008). In the last years, many studies on nitrogen balance in agriculture have been conducted, with comparisons among diverse management systems and crops. Considering the importance that sustainability is assuming in agriculture, these studies investigate if some crops are more effective than others in reducing nitrogen leaching, or the emission of nitrogen in atmosphere. Nitrogen is one of the major nutrients that sustains plant growth and development, and the main nutrient that is supplied to agricultural lands by organic and mineral fertilization. Most of the atmosphere, approximately 78%, is diatomic nitrogen (N_2), which is unavailable to most organisms because of the strength of the triple bond that holds the two nitrogen atoms together (Galloway, 2004). It can be usable for plants only if converted by some species of Bacteria or Archaea. A limited number of vegetal species can host these microorganisms, the most notorious are in the legumes family (*Fabaceae spp.),* that was the first case in which a process called "biological nitrogen fixation” or BNF, was discovered and studied in the 19th century by the German agronomist Hermann Hellriegel (1888). In figure 1 the anthropogenic interferences on the nitrogen cycles are shown.

Fig. 1: How the nitrogen cycles has been modified by human activities, Gruber and Galloway (2008)



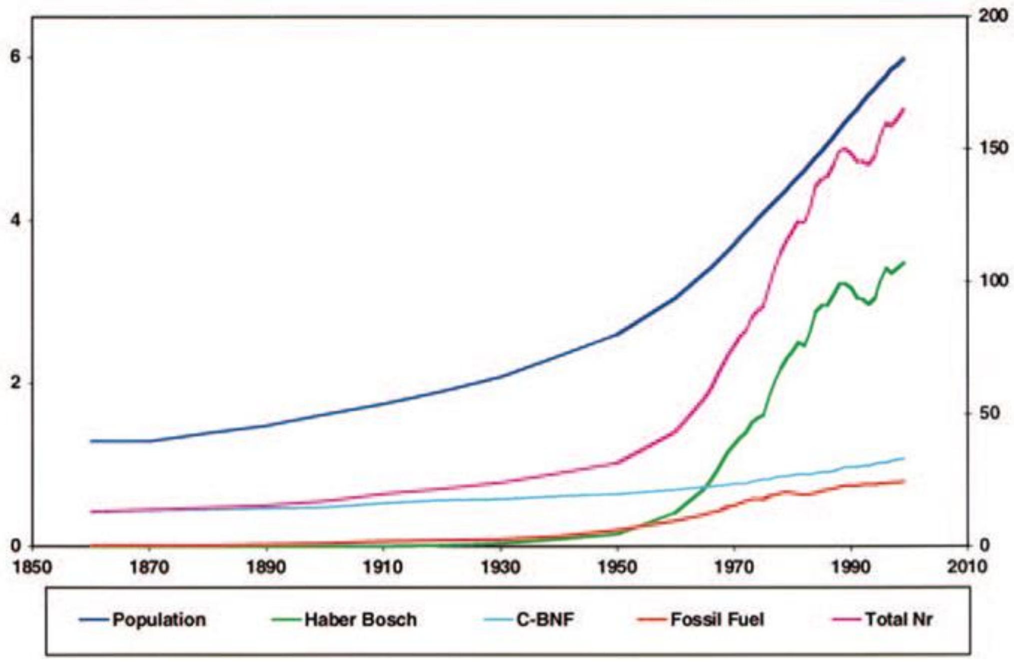
The amounts of reactive nitrogen furnished by BNF, as exhaustively reviewed by Smil (1999), play an important role in agricultural systems. Rhizobium associated with seed legumes (e.g., beans and peas) can fix nitrogen at rates ranging from 3.102 to 3.104 mg N m^2. In most of the cases, these rates are on the order of 3.104 to 4.103 mg N m^2. Rhizobium associated with leguminous forages (e.g., alfalfa, clover) have higher average rates, from 1.104 to 2.104 mg N m^2. Non-Rhizobium N-fixing organisms associated with some crops (e.g., cereals) and trees have ranges from 2.103 to 5.102 mg N m^2, while cyanobacteria associated with rice paddies and endophytic diazotrophs associated with sugar cane can fix 2.103 to 3.103 mg N m^2 and 5.103, respectively

(Smil,1999). These consistent amounts of reactive nitrogen, that these crops can grant to the natural nitrogen balance, would not have been sufficient to sustain current agricultural yields, that are largely increased respect to pre-industrial times (FAO, 2001; Tilman *et al*. 2002). Historically natural ecosystems and agricultural lands were nitrogen-limited systems, and with low productivity. The Industrial Revolution changed this situation dramatically, leading to huge alterations in the global nitrogen cycle, with an excessive availability of reactive nitrogen. For long times in human history, until the 20^{th} century, BNF was the only way to exploit atmospheric nitrogen, that was a precious nutrient provided by animal manure and not accessible at low costs (Sutton *et al.*, 2011). This situation changed thanks to the invention of Haber Bosch process (1911), according to Nature the most important scientific invention of the 20^{th} century. This industrial process permits to synthetize fertilizers, converting atmospheric nitrogen (N_2) to ammonia (NH_3) by a reaction with hydrogen (H_2), using a metal catalyst under high temperatures and pressures. Fritz Haber and Carl Bosch found that a mixture of Fe_2O_3 and Fe_3O_4 catalyzes this reaction at temperatures in the range of 400 °C to 600 °C :

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3 \quad (\Delta H = -92.4\ kJ\cdot mol^{-1})$$

This great availability of synthetized nitrogen allowed to increase agricultural production and started the Green Revolution, which has been sustaining world economy and the stable increase of global population since now. The importance of the Haber Bosch process has been reassumed by Galloway *et al.* (2003). In Figures 2 and 3 are depicted the trend of reactive nitrogen from the industrial revolution and in the last decades.

Fig. 2: Reactive nitrogen in the world from 1850 to 2000, Galloway et al. (2003) Global population trends from 1860 to 2000 (billions, left axis) and reactive nitrogen (Nr) creation (teragrams nitrogen [Tg N] per year, right axis). "Haber-Bosch" represents Nr creation through the Haber-Bosch process, including production of ammonia for nonfertilizer purposes. For 1920, 1930, and 1940, we assumed that global total Nr production through the Haber-Bosch process was equivalent to global anthropogenic fertilizer production (Smil 2001). For 1950 onward, data on Nr creation through the Haber-Bosch process were obtained from USGS Minerals (Kramer 1999). "C-BNF" (cultivation-induced biological nitrogen fixation) represents Nr creation from cultivation of legumes, rice, and sugarcane. The C-BNF rate for 1900 is estimated to be approximately 15 Tg N per year (Vaclav Smil, University ofManitoba,Winnipeg, Canada, personal communication, January 2002). The C-BNF rates for 1860, 1870, 1880, and 1890 were estimated from population, using the 1900 data on population and Nr creation. Reactive nitrogen in the world from 1960 to 2010, Galloway et al.(2003) For 1961–1999, Nr creation rates were calculated from crop-specific data on harvested areas (FAOSTAT 2000) and fixation rates (Smil 1999). Decadal data from 1910 to 1950 were interpolated between 1900 and 1961. "Fossil fuel" represents Nr created from fossil fuel combustion. The data from 1860 to 1990 are from a compilation from Elisabeth Holland, based on Müller (1992), Keeling (1993), and Holland and Lamarque (1997). These data agree well with those recently published by van Aardenne and colleagues (2001) for decadal time steps from 1890 to 1990. The data for 1991 to 2000 were estimated by scaling emissions of nitrogen oxides to increases in fossil fuel combustion over the same period. "Total Nr" represents the sum created by these three processes.

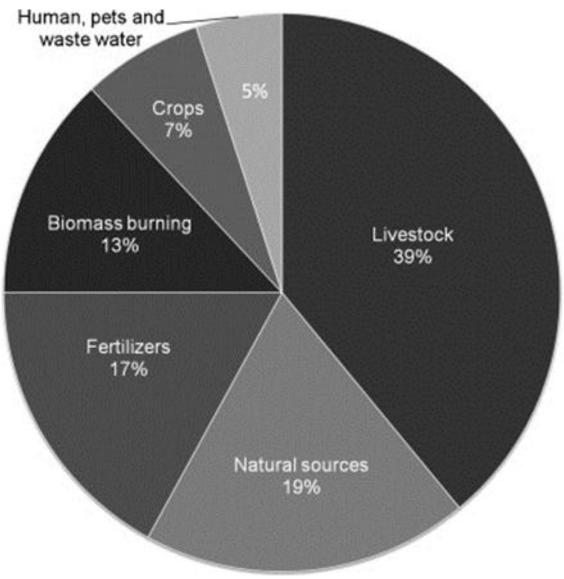


Rising agricultural demands have been satisfied by an escalation in reactive nitrogen (Nr) creation, thanks to Haber Bosch process, about 100-121 Tg N year^{-1} (FAO, 2006). Synthetized “Haber-Bosch” fertilizers are urea-products that differ from organic fertilizers, manure and others (Edmeades, 2003). These products have many advantages respect to traditional organic fertilization, because they are rich in essential nutrients and always ready for immediate supply of nutrients to plants if situation demands, and they have an higher concentration of nutrients per weight, making their management easier. For these reason organic fertilizers are more expensive than chemical ones and, as relieved in agricultural statistics (FAOSTAT, 2006), less used. With the Haber Bosch process started the fertilizers industry and reactive nitrogen in the environment increased largely Nr creation is still accelerating, a trend unlikely to change in the near future, due to economic growth and change of diet in the undeveloped countries (Galloway *et al.*, 2008). Given expected trends in population, demand for food, energy and agricultural practices, nitrogen fluxes are going to increase, and humans are likely to be responsible for doubling the turnover rates not only of the terrestrial nitrogen cycle but also of the nitrogen cycle of the entire Earth (Gruber and Galloway, 2008). The change in human diet with a shift towards meet and the industrialization were the two main causes that lead to the so defined “nitrogen bomb”, that consists in the excessive spread of reactive nitrogen, which leads to serious environmental consequences.

1.2 Statistics on ammonia emission

Ammonia is a recognized pollutant gas that is emitted mainly from manure management, which neutralizes atmospheric sulphur dioxide (SO_2) and atmospheric nitrogen oxides (NOx) to form particulates (Asman *et al.*, 1998). Ammonia includes both gaseous and molecular ammonia (NH_3) and compounds containing the ammonium ion (NH_4^+), with the sum of both ammonia forms being termed NHx (Sutton *et al.*, 2008). Ammonia NH_3 and his particulate form NH_4^+ may be transported in the environment via wet and dry deposition. Dry deposition is usually near the source of ammonia emissions, wet deposition usually transports the particulate NH_4^+ over long distances. Although ammonia is not a greenhouse gas (GHG), it may indirectly contribute to agricultural emissions of nitrous oxide (N_2O), a potent GHG with a global warming potential of approximately 300 times that of CO_2 (Berg *et al.*, 2006). Another well-known negative effect caused by ammonia pollution is the particulate NH_4^+ influence in creating notorious PM_{10} and $PM_{2.5}$ particulates, which are an health hazard (McCubbin *et al.*, 2002). Besides having an acute toxic potential, NH_3 and NH_4^+ may disturb vegetation by secondary metabolic changes due to increased nitrogen uptake and assimilation leading to higher susceptibility to abiotic (drought, frost) and biotic (pests) stresses (Fangmeier *et al.*, 1994). In figure 4 the global repartition of ammonia sources are represented: ammonia is globally produced for a large part by livestock manure (39%) and secondary from mineral fertilizers (17%). Other sources of ammonia volatilized are biomass burning (13%), natural sources (19%) crops (7%) and a general part constituted by human, pets and waste waters (5%).

Fig. 3: Repartition of sources of global ammonia emission, Philippe et al. (2011)



Agriculture is the major source of atmospheric ammonia, contributing 55-56% of global NH_3 emissions (Bouwman *et al.*, 1997), and livestock management is the main responsible for ammonia pollution (Aneja *et al.*, 2001; Battye *et al.*, 1994). In Europe, the emission of ammonia that comes from agriculture is particularly high, more than 70% of total European emissions (Erisman *et al.*, 2003). The majority of nitrogen losses from manure management systems are in the form of ammonia emission. Ammonia gas is formed when urea in urine combines with the urease enzyme, in feces or soil, and hydrolyzes to form ammonium, which may be converted to ammonia gas (Varel *et al.*, 1997). Different key processes of manure management are responsible for ammonia pollution: the production of manure in livestock buildings accounts for 41% of the total emissions, the storage is responsible for 24%, and the spread of manure on field accounts for 35% (Oenema *et al.*, 2007). Most of the nitrogen contained in manure is in the ammonium form NH_4+, that responds to the chemical equilibrium:

$$NH_4^+(aq) \rightleftharpoons NH_3(aq) + H^+(aq)$$

Atmospheric ammonia (NH_3) is a very important constituent of the environment because it is the dominant gaseous base specie present in the atmosphere (Aneja *et al.*, 2001). Ammonia is a concern for European agriculture, that as an higher concentration of animal husbandry respect to the rest of the world. European directive have posed several limits to animal husbandry in order to face this challenge. There is a great interest in understanding critical processes that cause ammonia volatilization, that regard the three phases of manure management: housing, storage and application on agricultural land. The presented table 1 shows that almost 30% of European emissions are from storages, the core of the first chapter of this thesis, and that a set of measures should be implemented because of the high differences among countries, that can be explained with diverse management systems.

Table 1: Total amount of nitrogen excreted during housing and total N losses from manure management systems for the EU-27, expressed in kg N ha^{-1} of agricultural land (Oenema et al., 2007)

Member State	In-house N excretion	N losses from manure storage systems					
		NH_3	N_2	N_2O	NO	N leaching	Total
Austria	38	6	2	0.4	0.2	2	11
Belgium	156	25	7	1.3	0.8	5	40
Bulgaria	16	3	1	0.1	0.1	1	5
Cyprus	96	19	6	0.6	0.5	4	30
Czech. Rep	41	8	2	0.3	0.2	2	12
Denmark	92	15	3	0.6	0.4	2	21
Estonia	24	4	2	0.2	0.1	1	7
Finland	40	6	2	0.4	0.2	2	11
France	39	7	3	0.4	0.2	2	12
Germany	71	14	2	0.3	0.4	2	18
Greece	15	3	1	0.1	0.1	1	5
Hungary	24	5	2	0.2	0.1	1	8
Ireland	54	8	2	0.2	0.3	1	11
Italy	48	11	3	0.4	0.3	2	16
Latvia	14	3	1	0.2	0.1	1	5
Lithuania	19	4	1	0.1	0.1	1	6
Luxembourg	53	9	3	0.5	0.3	2	15
Netherlands	203	27	4	1.7	1.0	5	40
Poland	34	7	3	0.4	0.2	2	12
Portugal	32	6	2	0.2	0.2	2	11
Romania	19	4	1	0.1	0.1	1	6
Slovakia	23	5	1	0.1	0.1	1	7
Slovenia	73	16	3	0.5	0.4	3	23
Spain	24	5	1	0.2	0.1	1	8
Sweden	37	7	2	0.3	0.2	1	10
U. Kingdom	35	7	2	0.3	0.2	1	11
EU-27	40	7	2	0.3	0.2	1	12

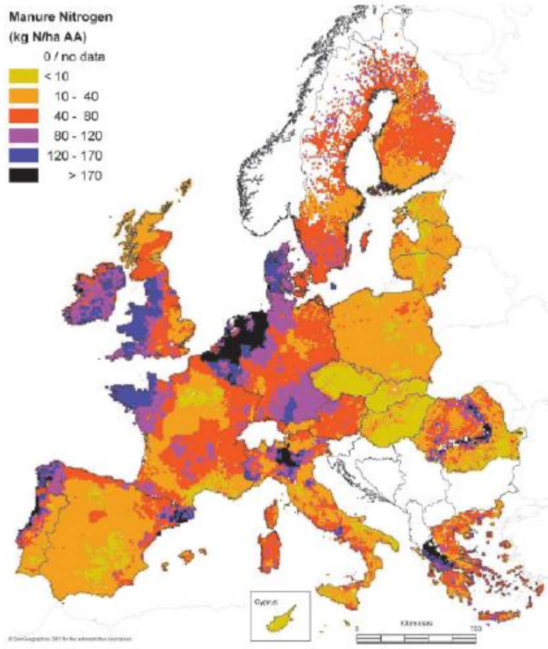
Results for Malta are not shown because of inconsistent statistical data (results of MITERRA-EUROPE).

1.3 The nitrogen challenge and manure management

With the increase of fertilizers production during the 20th century, nitrogen that comes from livestock manure begun to be seen as a problem and not as a resource. Manure is defined as animal feces and urine plus materials such as bedding and water. Slurry is defined as a liquid manure, with a concentration of solids less than 12% (Pain and

Menzi, 2003). Slurry is the main product of manure management in Europe, because of the management technique that is adopted in animal husbandry, especially in pigs production. The global production of manure has reached an impressive amount, but chemical fertilizers are preferred because of their faster availability for crops. The production of synthetic fertilizers and animal manure are expected to increase in the coming decades, particularly in developing countries. The source of NH_3 emissions from manure management is the N excreted by livestock. Typically, more than half of the N excreted by mammalian is in the urine, and between 65% and 85% of urine N is in the form of urea. Globally, manure contributes for 8 million tons of NH_3 emissions, hence losses via atmosphere are around 23% of distributed slurry (19-29%) (Bouwman *et al.*, 2002). The volume of animal manure applied annually to crops in developed countries is around 33 million tons N per year. The total amount of N excreted in European Union rise from 7-8 Tg in the early 60's to 11 Tg in the late 80's. Then it tended to slightly decrease or remain stable, depending on the kind of animal.(Oenema *et al.*, 2007). However, as shown in figure 5, the European problem of slurry management is related with the heterogeneous distribution of livestock, and not with the manure amount.

Fig. 4: Animal husbandry is concentrated in some industrialized areas of European Union, Oenema et al. (2004)



The European meat production is concentrated in few European regions that correspond to areas with the amount of manure distributed on agricultural soils and, generally, nitrogen vulnerable zones according to the legislation. There are large differences depending on countries and within countries with respect to nitrogen emissions. This is not only due to differences in livestock densities, but also the kind of management systems is important. Emission are highest from intensive agricultural systems in the North of Europe (Oenema *et al.*, 2007). Many are the worries that come from excessive of reactive nitrogen. In the reactive form, nitrogen is transported easily between air, water and soils, following the nitrogen cascade (Galloway, 2003).

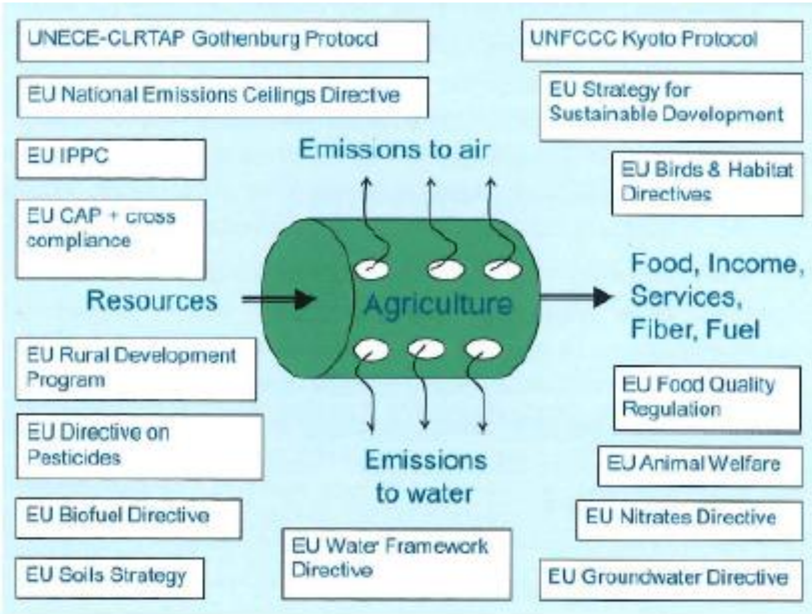
Fig. 5: Nitrogen bomb can lead to algal bloom in water bodies, Anonymous

The cascade is interrupted only when nitrogen is stored in inaccessible places or converted back in N_2. Basically the reactive nitrogen can affect these three sector of the biosphere: atmosphere, soils, water bodies. The negative effect in atmosphere is due to the conversion of ammonia to nitrous oxide, a potent greenhouse gas, the toxic effect of ammonia, that is transported via wet deposition over long distances, and can be harmful for human health. Reactive nitrogen, in the form of NO_X, is an air pollutant that promotes the creation of ozone and smog, which, interacting with the lining of the lungs, can trigger respiratory conditions ranging from asthma to even death after chronic exposure (Braun, 2007). In soils there is a problem due to acidification induced by ammonia deposition. Ammonia reacts with acids in the atmosphere to form ammonium salts, that are deposited on soils leading to acidification. For water bodies, the problem of eutrophication is particularly pronounced, and highly affected by nitrogen inputs from agriculture. Nitrogen leaching is the key process, but also runoff contributes to enhance beyond a critical point the concentration of reactive nitrogen in water. The ecosystem's response to the addition of artificial or natural nutrients, mainly phosphates, through detergents, fertilizers, or sewage, to an aquatic system. One example is the "bloom" or great increase of phytoplankton in a water body as a response to increased levels of nutrients One of the worst problem, eutrophication of water bodies, has been depicted in figure 6. Negative environmental effects include hypoxia, the depletion of oxygen in the water, which may cause death to aquatic animals. In order to reduce the effect of the nitrogen pollution, researchers have focused mitigation strategies to reduce the impacts of nitrogen sources in agriculture. These strategies have been promoted by European Union, with a set of legislative acts.

1.4 Directive and limits for nitrogen in agriculture

With the increasing concern about the impacts of livestock production growth on natural resources and human health, national and international regulations went into effect to deal with these issues. The scientific community and European Union have indicated the management of reactive nitrogen has one of the most important achievement to be implemented. European environmental policies and measures specifically aim at decreasing leaching of nitrates in water bodies and emission of ammonia in the atmosphere (Oenema *et al.*, 2007). Different aspects concerning agricultural sustainability are treated in legislative acts, and the influence on manure management practices is more or less recognized in each of them. Nowadays, agricultural activities, and especially the use of animal manure and fertilizers, are affected by a number of legislative acts, that are represented in figure 7.

Fig.6: Overview of the EU policies implemented in agriculture that regard directly or indirectly the use of fertilizers and animal manure and/or the emissions of nutrients to the environment, Oenema et al.(2004)



Five categories of European policies and measures are very important for manure management: Agenda 2000, Water related directive, Air related directive, Nature conservation legislation, Animal welfare regulation. For the content of this thesis, nitrogen emission from slurry management, great importance has been given to these issue thanks to Nitrate Directive, followed by other legislative acts as shown in table 2.

Table 2: Background on the EU policy on gas emissions, Salazar (2014)

Year	Directive	Description
1996	96/61/EC	IPPC Directive. Installations need operating permits. Best available techniques (BAT) definition.
2001	2001/81/EC	NEC Directive. All 28 EU Member States have to report information annually on emissions.
2008	2008/1/EC	IPPC Directive reform. Installations need operating permits. Installations need to comply with environmental quality standards described in other Directives. Installations need to apply the BAT.
2010	2010/75/EU	IED Directive.

The reform of the Communitarian Agricultural Policy (CAP) for 2014-2020 has increased the importance of greening and measures to face the nitrogen challenge, and find innovative solution using agricultural resources. Considering the European scenario, excess of nitrogen in the environment costs the European Union (EU) between 70 billion and 320 billion euro per year (Sutton, 2011). Agriculture has been recognized as the major driver of the global nitrogen cycle, and most of the efforts to reduce reactive nitrogen in the environment are addressed to the agriculture. The concern about the nitrate in the environment begun in 1970s in relation to eutrophication problems. The first act in this legislative framework was the Council Directive75/440/EEC of 16 June 1975, concerning the quality required of surface water intended for the abstraction of drinking water in the Member States, followed by the Council Directive 80/778/EEC of 15 July 1980, relating to the quality of water intended for human consumption (Conrad, 1990).The nitrate directive (1991) is the major legislative reference to face the nitrogen challenge. The nitrate directive, an integral part of water framework directive, aims to protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices. It concerns all the aspects of manure management, and obliges to manage the European agriculture in an environmental friendly way. The CAP has posed limits to the use of nitrogen in vulnerable zone, and it has stimulated the greening, then the applicable measures to reduce pollution and increase sustainability. The European approach to the nitrogen problems was an incitement to consider the effect of ammonia pollution on global scale. Gothenburg protocol (1999) to abate acidification, eutrophication and ground level ozone is the milestone for regulations on ammonia emission and established national emission ceilings for Sulphur Dioxide, Nitrogen Oxides, Ammonia and Volatile Organic Compounds (Kelly *et al.*, 2010). The report of IPCC has completed the framework with a set of measures, the BAT (Best Available Techniques) that farmers should implement in order to achieve proposed environmental targets. One of these strategies to reduce nitrogen pollution is Agro-forestry, that will be treated exhaustively in the last chapter of this thesis. It has been incentivized by the CAP, and the European Commission (EC) has prescribed an increase in renewable energy generation, of which biomass currently contributes 66%. Woody biomass has been financed by the European Agricultural Fund for Rural Development, in order to reach sustainability targets within 2020. The adoption of Short rotation coppice crops can be seen as a core point in the new European policy on agriculture (2014-2020), as a consequence of the UE regulation n. 1310/2013. The first pillar of CAP (43.45 billion euro) concerns the income support, which is an economic aid that must be associated with seven specific duties for farmers. Among these, greening is really important because 30% of the first pillar financial fund is bound to services concerning ecological conservation and measures to face climate changes. Short rotation coppice, that should occupy at least 5% of the farm land, is a measure that satisfy the greening point. The second pillar of CAP (13.82 billion euro) regards the policy for rural development, that can be integrated with the first pillar. Short rotation coppice is considered a step towards a carbon-free economy. Hence 30% of the second pillar's financial funds will be given for some environmental measures, among these soil protection and strategies to face climate changes.

1.5 The phases of manure management: storage and distribution on agricultural land

It is necessary that the slurry kept from the animal houses become mature in storage. Adequate storage facilities are necessary to handle the larger volumes of slurry, save nutrients and reduce environmental risks. Slurry, depending on the region and country, must be kept for long periods in storages, from 3 to 9 months. Storages for liquid slurry can be tank or lagoon. A tank is a vessel that usually has a circular shape and it is made by enameled steel, concrete or wood panels. Lagoon is a large rectangular or square shaped structure with sloping earth bank walls. In this care, a great care is placed in waterproof the soil below the lagoon, in order to avoid infiltration in groundwater. Recently, the disposition of European Union forecast the adoption of circular tanks. The depth of the storage is an important parameter, because deeper is the storage and minor is the surface exposed to the atmosphere. For tanks the depth can vary from 3 to 5 m, whereas for lagoon is generally lower, with a depth around 2-3 m. The storage of slurry is the topic of the first chapter of the thesis, and it includes a modelling approach to simulate ammonia emissions. Scientific literature on this theme is based on the 90's and 2000's scientific works done in Northern Countries. Due to the effective possibility to abate emissions from storages, a number of studies have been published and some reviews have indicated reliable range of values for ammonia emissions. The NH_3 emissions increase with concentration of TAN in slurry, and TAN concentration is related to the animals diet. Surplus of nitrogen in diets is excreted as urea, and therefore feeding practice significantly affects urea concentrations (Phillips *et al.*, 2001). Ammonia losses are much higher from manure stored in open tanks and lagoons than in manure stored under covers (Bussink and Oenema, 1998). Losses from slurry stored outdoors increase with temperature, surface area, wind velocity, pH and storage period. The temperature of stored livestock slurry largely parallels ambient temperature (Petersen and Sommer, 2011), although temperature changes are dampened with depth in store. An increase in temperature increases the mineralization of organic nitrogen in slurry, thus increasing the production and emission of NH_3. As suggested by Ni (1999) a crucial factor that determine ammonia emission from storages is the emitting area exposed to the free atmosphere. For manure storages are recommended structures that increase the ratio depth/surface. This is the most important advantage of tanks respect to lagoons as storage structures. Data suggest that emissions per unit area are similar for lagoons and above-ground tanks, but in reason of the greater emitting area of lagoons the adoption of tanks leads to a reduction in NH_3 emissions (Nicholson *et al.*, 2002). Covering manure stores is another cost effective measure to reduce ammonia emissions. Several types of manure storage covers have been reported in the literature, ranging from natural crusts in manure storages with high solids content to straw, wood chips, oil layers, expanded clay, wood, semi-permeable and sealed plastic covers (Arogo *et al.*, 2002). The effectiveness of the manure storage cover depends on many factors, including permeability, cover thickness, degradability, porosity and management (Guarino *et al.*, 2006). Ammonia volatilization from slurries tanks can be reduced in this way or by acidification (Webb *et al.*, 2005). However, acidification is not feasible because of the sophisticated technologies adopted, high costs, and inconveniences of environmental pollution (Canh *et al.*, 1998). A non-expensive option is the natural crust formation, which may occur for slurries with high dry matter content. For example, crusting is unlikely to occur on stores with a slurry DM content of <1% (Misselbrook *et al.*, 2005). Cattle slurry often forms a natural crust of slurry organic matter, whereas pig slurry will not normally have a surface crust unless established by the addition of chopped straw (Sommer *et al.*, 2009). Some studies have cleared that the overall increase in crust thickness is matched by the cumulative evaporative water loss from the tank (Smith *et al.*, 2007). The third part of the slurry management chain is the distribution of slurry on field. Most of the volume of animal manure produced in Europe is applied to fields as slurry (Menzi, 2002). There are a number of spreading techniques that have different impact on ammonia emissions (Webb *et al.* 2010). The conventional method of spreading slurry, the surface broadcasting by splash plate applicator, is rapid and inexpensive. However, this technique has many negative consequences, with large ammonia losses, damage grass swards (Christie, 1987; Wightman *et al*., 1997), contamination of crops with microorganism that can impede silage fermentation (Anderson and Christie, 1995; Steffens and Lorenz, 1988), high runoff of nitrogen (Uusi-Kamppa and Heinonen Tanski, 2001), and gives a bad crop response that discourage farmers (Bittman *et al.*, 1999). Trailing hose consists in pumping the slurry through numerous hoses (40-50 mm diameter)positioned along a boom at a spacing of around 30 cm. The slurry is placed directly on soil, and left in 10-15 cm wide bands. Trailing hose technique reduces the ammonia emissions thanks to the banding of slurry. These effect is particularly pronounced when the banding of slurry is done under crop (Klarenbeek and Bruins, 1991) Surface runoff is also limited by this technique, that concentrates the slurry in bands (Lau *et al.*, 2003). Trailing shoe is a kind of semi-injection. Shallow furrows are cut in the ground and the furrow are filled with slurry. Misselbrok *et al.* (2002) reported an explained 47% of the variance in NH_3 emission using trailing shoe technique. In Huijsmans review of 45 field results it was showed that 50% of the variation in the emission was related with this technique. Injection is the technique that presents the greatest abatement of ammonia emissions. As the trailing hoses, the slurry is pumped through hoses, each connected to a tine or a disc. Injection is almost impossible in some kind of soils, for example in very heavy clay soils. Rodhe and Etana (2005) demonstrated that emissions from injection were half of that ones with trailing hose. Other studies (Hansen *et al.*, 2003; Huijsmans 2003; Rodhe *et al.*, 2004) have confirmed the abatement of ammonia emission that is related with the injection techniques, but they have also underlined the limits of this technique, that depend on soil characteristics, worked depth and required energy. The last option for slurry is the incorporation by cultivation of the soil, operated by moldboard and chisel plough and by disc harrow. Thompson and Meisinger (2002) found a great reduction of emissions with this technique. Basically, from the analysis of literature, we can affirm that the cost of the spreading technique is linked with the effectiveness in reducing ammonia emissions. The abatement of emission following the application of slurry is still a priority to reduce ammonia emission on European scale (Webb *et al.*, 2005). Despite the technique, the amount of emission is variable and dependent also on a number of factors involved in ammonia volatilization process. The effect of these factors has been considered in many studies during the nineties, each of which included two or three factors (Horlacher and Marschner,1990; Sommer *et al.*, 1991; Sommer *et al.*, 1991; Smith and Chambers, 1995; Braschkat *et al.*, 1997; Menzi *et al.*, 1997). Ammonia losses following field application, and hence the amount of nitrogen that enters into the soil nitrogen cycle, are dependent on climate and crop height (Thorman *et al.*, 2008). The diverse meteorological factors, in order of importance, air temperature (direct solar radiation), wind speed, rainfall, give a reduction in percentage of the ammonia emission. Indeed, the chemical characteristics of slurry are crucial in determining the potential for ammonia emissions, with a crucial role played by total ammonia nitrogen and solid matter concentration. The volatilization has been shown to be significantly and directly correlated to dry matter content (DM). Sommer (2003) identified slurry DM as a factor influencing infiltration of slurry into soil, Huijsmans (2003) summarized that slurries with higher TAN contents are normally associated with higher ammonia emissions, and that there is a good correlation between concentrations of ammonia and TAN in slurry. The pH of slurry has an essential role on the emission of NH_3, and it is controlled by a number of acids and bases, of which the most important are volatile fatty acids (VFA), total inorganic carbon (TIC) and total ammonia nitrogen (TAN) (Sommer and Husted, 1995). Higher is the pH, higher the ammonia emission in the same time of exposure Certainly the ammonia emission from slurry are influenced by the speed of infiltration in soil, in other words, less is the exposure to the atmosphere, less are the emissions. The combination of all the above mentioned factors, management factors plus environmental variables, can account for a large but very variable proportion of the plant available N: from a few percent to 100% of TAN (Webb *et al.*, 2005).

1.6 Prospective of the thesis

In the last decades strategies to reduce the effect of reactive nitrogen in the environment have been studied and implemented, among these strategies the adoption of woody biomass has been considered an interesting option. The most desirable abatement strategies should respect the idea of sustainability, that is the intersection of economical, technical, environmental and social spheres. In this thesis, studies on the storage of manure and its distribution on field have been done, and a special focus has been posed on Short Rotation Coppice crops (SRC), performing experiments on field and developing a modelling approach. These crops, for Europe primarily Willow (*Salix spp.)* and Poplar (*Populous spp*.), could be a viable abatement strategy to mitigate nitrogen pollution achieving a reasonable nitrogen balance and enhanced yields (Dimitriou *et al.*, 2011). The topic of this thesis is huge and included both storages and distribution on agricultural land. The European Directives and other international initiatives have placed attention on the implementation of techniques to improve manure management.

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2. Nitrogen emissions from slurry storages

Nitrogen losses analyzed in this works are mainly ammonia emissions, from storages and from volatilization following slurry spreading. Secondary emission are of N_2O and mainly occur from slurry spreading (nitrous oxide emissions from slurry storages are considered negligible). Mitigation techniques are measures that modify the influencing factors in limiting ammonia emission. In this context a number of techniques, concerning each of the three phases of manure management, can be found. In storage and application of livestock manure is essential to know the ammonia losses in order to efficiently improve the use of nitrogen for crop production (Carozzi, 2013). Manure that exits from animal buildings is a mixture of feces and urine plus bedding, spilt feed, spilt drinking water and water used for washing. Manure collected from animal houses, according to agricultural regulations, must be kept in storages (tanks or lagoons) for hygienic stability and environmental safety. These structures have to be dimensioned to receive an amount of slurry proportional to the consistency of livestock. Due to the effective possibility to abate emissions from storages, a number of studies have been published and some reviews have indicated reliable range of values for ammonia emissions. The NH_3 emissions increase with concentration of TAN in slurry, and TAN concentration is related to the animals diet (Portejoie *et al.*, 2002). Surplus of nitrogen in diets is excreted as urea, and therefore feeding practice significantly affects urea concentrations (Phillips *et al.*, 2011). Reduce ammonia from slurry storages is quite simple, it could be done by a range of measures including reducing the surface area to volume ratio of the storage (20-50% abatement) to fitting a solid roof, tent or lid to the store (80% abatement), or with the adoption of fluctuant covers. A number of materials have been tried in these years for this purpose, among these the most important were:

peat, clay granules, oil, straw, floating poly ethylene film, corn stalk covers, polystyrene, permeable synthetic cover, pine bark, prune wood, maize stalks. Ammonia losses are much higher from manure stored in open tanks and lagoons than in manure stored under covers (Bussink and Oenema, 1998). Losses from slurry stored outdoors increase with temperature, surface area, wind velocity, pH and storage period. The temperature of stored livestock slurry largely parallels ambient temperature (Petersen and Sommer, 2011), although temperature changes are dampened with depth in store. An increase in temperature increases the mineralization of organic nitrogen in slurry, thus increasing the production and emission of NH_3. As suggested by Ni (1999) a crucial factor that determine ammonia emission from storages is the emitting area exposed to the free atmosphere. For manure storages are recommended structures that increase the ratio depth/surface. This is the most important advantage of tanks respect to lagoons as storage structures. Data suggest that emissions per unit area are similar for lagoons and above-ground tanks, but in reason of the greater emitting area of lagoons the adoption of tanks leads to a reduction in NH_3 emissions (Nicholson *et al.*, 2002). Covering manure stores is another cost effective measure to reduce ammonia emissions. Several types of manure storage covers have been reported in the literature, ranging from natural crusts in manure storages with high solids content to straw, wood chips, oil layers, expanded clay, wood, semi-permeable and sealed plastic covers (Arogo *et al.,* 2002) The effectiveness of the manure storage cover depends on many factors, including permeability, cover thickness, degradability, porosity and management (Guarino *et al.*, 2006). Ammonia volatilization from slurries tanks can be reduced in this way or by acidification (Webb *et al.*, 2005). However, acidification is not feasible because of the sophisticated technologies adopted, high costs, and inconveniences of environmental pollution (Canh *et al.*, 1998). A non-expensive option is the natural crust formation, which may occur for slurries with high dry matter content. For example, crusting is unlikely to occur on stores with a slurry DM content of <1% (Misselbrook *et al.*, 2005). Cattle slurry often forms a natural crust of slurry organic matter, whereas pig slurry will not normally have a surface crust unless established by the addition of chopped straw (Sommer *et al.*, 2009). Some studies have cleared that the overall increase in crust thickness is matched by the cumulative evaporative water loss from the tank (Smith *et al.*, 2007). Acidification of manure is a well-known treatment for reducing NH_3 emissions (Amon *et al.*, 1997): using additives to acidify slurry is a quite controversial topic that presents advantages but also weaknesses (Kai *et al.*, 2007). Although acidification of manure is an obvious treatment to mitigate NH_3 emissions from livestock production, the risk of foaming and potential hazards associated with the use of acids (Borst, 2001) for a period discouraged the use of additive in practice (Sommer, 2013). In this chapter a modelling approach to simulate ammonia emission from slurry storages is presented. The proposed mechanistic model is written in a simple declarative language, SEMoLa, and it has been used for scenarios assessment based on climate, management techniques and regulations. An extended abstract on this model has been presented to the 18th Nitrogen Workshop in Lisbon “The Nitrogen challenge: building a blueprint for nitrogen use efficiency and food security”(30 June – 3 July 2014).

Publication prepared for the Italian Journal of Agrometeorology

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A model to assess ammonia emission from pig liquid manure storage with applications to Denmark and Italy

Abstract

Ammonia is a recognized pollutant gas that mainly comes from agriculture. In Europe, liquid manure management has a prominent role in ammonia emission, with the storage of slurry representing one third of the ammonia emission from manure management. The magnitude of the problem have led to a number of directives and limits for animal husbandry, and the assessments of ammonia emissions still suffer from considerable uncertainties. Modelling ammonia emission can give an important contribute in quantifying nitrogen pollution, and so implementing abatement strategies for slurry storages. This study is about modelling ammonia emission from storages of liquid slurry, tanks or lagoon. A new mechanistic model has been developed and used to simulate the ammonia emission from pig slurry storages in Denmark and Italy, two countries that have an important development of intensive livestock farms. The aim of this new model stays in the improvement of the slurry production module, and in its easy usability for stakeholders. The results have been a sensitivity analysis to identified crucial parameters for ammonia volatilization, and the assessment of the emissions from pig slurry storages, using Danish and Italian meteorological data.

Keywords: ammonia emission, nitrate directive, manure management, modelling

Sommario

L'ammoniaca è un noto gas inquinante principalmente emesso dall'agricoltura. In Europa, la gestione degli effluenti d'allevamento riveste un ruolo principale nell'emissione di ammoniaca. Questo importante problema ha portato come conseguenza a numerose direttive e limitazioni per l'attività zootecnica, ma vi è ancora considerevole incertezza nella stima delle emissioni. Modellizzare le emissioni di ammoniaca può dare un importante contributo nel quantificare l'inquinamento da azoto, in modo da implementare strategie di mitigazione efficaci. Questo lavoro riguarda le emissioni di ammoniaca da stoccaggi di liquami, lagoni oppure vasche. Un nuovo modello meccanicistico è stato sviluppato e usato per simulare le emissioni provenienti da stoccaggi di effluenti suini in Danimarca e Italia, due paesi che presentano un grande sviluppo degli allevamenti intensivi. I risultati sono stati un'analisi della sensibilità che ha identificato i parametri cruciali nella volatilizzazione dell'ammoniaca, e nella valutazione delle emissioni dagli stoccaggi di liquame suino, usando dati meteorologici danesi e italiani. Lo scopo di questo modello è migliorare il modulo che simula la produzione dell'effluente, e nel garantire la facilità d'uso per gli operatori del settore.

Parole chiave: emissione di ammoniaca, direttiva nitrati, gestione degli effluenti, modellazione

Nomenclature table

Symbol	Unit	Definition
h	m	Altitude
$[NH_3]_{gas}$	g m^{-3}	concentration of ammonia in the boundary layer
$[NH_{3a}]_{ambient}$	g m^{-3}	concentration of ammonia in the atmosphere
[TAN]	g l^{-1}	total ammonia nitrogen
[TKN]	g l^{-1}	total Kjeldal nitrogen
l.u.	(-)	livestock unit
JNH_3	g m^{-2} s^{-1}	flux of ammonia
hm	m s^{-1}	mass transfer coefficient
kh	mol atm^{-1}	Henry’s constant
kd	(-)	constant of dissociation (in water)
ka	(-)	constant of dissociation (in slurry)
E	(-)	empirical corrective factor
Lat	degrees	Latitude
Ra	s m^{-1}	atmospheric resistance
Rb	s m^{-1}	resistance in boundary layer
Rc	s m^{-1}	resistance induced by slurry covers
U	m s^{-1}	wind speed
T	C°	Temperature
l	m	length of the fetch
$EmiNH_3$	g s^{-1}	emission of ammonia
SluP	l	slurry production
Nani	(-)	number of pigs
Kt	%	daily rate of excreta
Slu	m^3	slurry
ExcP	kg	excreta production
TS	%	total solids
Dilf	(-)	dilution factor

1 Introduction

Agriculture is the main source worldwide for the emissions of ammonia (Bouwman *et al.*, 1997). Ammonia is a recognized pollutant gas, which is a problem for human health and may cause acidification and eutrophication of natural ecosystems (Brandt *et al.*, 2011; Sutton *et al.*, 2011). Accurate inventories of agricultural NH_3 emissions are required to calculate national emissions, since they commonly account for more than 80% of the total emissions (EMEP, 2005). Among agricultural sources of ammonia, slurry management has a prominent role (Sutton *et al.*, 2008). There are different key processes of slurry management responsible for ammonia pollution: the excreta production in livestock buildings, the storage of slurry in tanks or lagoons, and its spread on field (Oenema, 2007). Slurry storages are characterized by a combination of feces, urine and wash-waters. This study is focused on ammonia emissions from slurry in open tanks, tanks and lagoons, which can range from 6 to 30% of total nitrogen in stored slurry, assuming that there is an emitting surface over the whole year (Sommer *et. al.*, 2006). In the Danish ammonia emission inventory it has been assessed that over the year 11, 4% of NH_3 in pig slurry transferred to the stores are emitted in atmosphere (Hansen *et al.*, 2008), whereas for Italy it has been assessed that 13,6% of ammonia in pig slurry transferred in stores is emitted in air over the year (Valli *et al.*, 2010). The process of ammonia volatilization from slurry or manure is well known (Arogo *et al.*, 2006), and it is influenced mainly by climate regime and chemical composition of slurry, but also depends on the portion of the slurry surface directly exposed to the atmosphere. Ammonia volatilization has been correctly described as a mass transfer process: the emission process is driven by the concentration gradient between the NH_3 in the air immediately adjacent to the surface $[NH_3]_{gas}$ and the ambient atmosphere $[NH_3]_{ambient}$. There are still different approaches to measure ammonia emissions, due to the high reactivity of ammonia compounds (Shah *et al.*, 2006), its great variability in space and time and tendency to bind with water (Ferrara, 2010). A number of methodologies have been adopted to assess ammonia volatilization, among these, methods that allow to easily estimate emission on regional scale are emission factors and models. Emission factors are convenient and easy to use, but they show weakness when measurements data are taken from diverse agro-ecological zones, characterized by different climates, animals races and management techniques (Arogo, 2003). In order to implement these important aspects, a modelling approach, based on System Dynamics Theory, has been adopted. A mechanistic model, usable at a farm scale, has been developed to improve ammonia emission assessment from slurry storages. The most important theories adopted in ammonia volatilization models are the two film theory and the boundary layer theory. The proposed model has been based on the Boundary Layer Theory, generally used in the models of NH_3 release from stored pig slurry (Ni, 1999). This theory is simpler than the two film theory, and includes only two steps of NH_3 mass transfer: the convective transfer from the manure surface to the free air stream, and the diffusion transfer inside the bulk slurry. This modelling approach has been applied to the comparison of ammonia emission from pig slurry storages, performing simulations for Denmark and the North of Italy (Po Valley). The purposes of this work are so defined: 1) Providing a new model to simulate ammonia emissions from slurry storages. This model aims to improve the lack of knowledge about the sub-model of manure production in previous models, which has been improved in a simple and usable way for farmers. 2) Using the model for a comparison between Italy and Denmark slurries management. Improving the Emission Factors for ammonia could be an interesting advance for this kind of studies (Reidy *et al.*, 2007).

2. Material and Methods

The model on ammonia emission has been developed in SEMoLa framework (Simple, Easy to use, Modelling Language; Danuso and Rocca, 2014), a software application for the development of simulation models and agro-ecological knowledge integration. A model to investigate NH_3 emissions and mitigation strategies should quantify excretal returns, manure distribution to outdoor storages, and climate conditions at least on a daily step, to capture interactions between environmental conditions and manure management (Petersen and Sommer, 2011). The importance of mechanistic models is related with the need of assessing quantitatively ammonia emissions, without expensive measurements that even could be not enough precise, as in the case of pH measurements on the surface of slurries (Blanes-Vidal, 2009). The model has been developed on hourly basis and divided in modules, as suggested by Ni (1999). The main convective module includes a part on pH dynamic that is linked with a manure production module. The module of manure production is functional to assess the size and the empting strategies of storages, coherently with the aim of this work: the development of a simple decision support model for farmers. The model can be adopted to simulate two kind of storages, tank or lagoon, and the manure production that occurs in different pig farms.

2.1 The convective module

Ammonia volatilization is a mass transfer process that has a magnitude proportional to the gradient of concentration of NH_3 in the air immediately adjacent to the surface $[NH_3]_{gas}$ and that in the ambient atmosphere $[NH_3]_{ambient}$ (Rachhpal–Singh and Nye, 1986):

$$J_{NH3} = hm * ([NH_3]_{gas} - [NH_3]_{ambient}) \qquad \text{(eq.1)}$$

hm, the mass transfer coefficient, is included in the resistances approach. A crucial task in developing an ammonia volatilization model is a reliable assessment of $[NH_3]_{gas}$ (Ni, 1999), the gaseous ammonia in the air layer adjacent to slurry surface (Sommer, 2013):

$$[NH_3]_{gas} = \frac{1}{\mathrm{Kh}} * \frac{[\mathrm{TAN}]}{1+\frac{10^{-\mathrm{pH}}}{\mathrm{Ka}}} \qquad \text{(eq.2)}$$

Where Ka is the constant of dissociation of ammonia in manure; Kh is the Henry's constant for ammonia; TAN is total ammonia nitrogen.

Slurry pH is of great importance in driving NH_3 emissions from slurry (Sommer and Husted, 1995). Especially the pH dynamics are crucial to determine emissions of ammonia. The amount of NH_3 gas dissolved in manure relies on pH and temperature. Modeling the spatial and temporal variations of pH in slurry is a complex task, and the work of Rachpal-Singh (1986) has suggested that emissions of NH_3 should be corrected for the change of pH that occurs in the first hours of exposition to atmosphere. Transport of TAN from the bulk of slurry to the surface is a combination of diffusion and convective movement, due to wind effect, differences in temperatures in different layers of slurry, and ebullition due to anaerobic degradation of organic components (Sommer *et al.*, 2006).

Differences in bulk slurry pH compared to surface pH can be explained largely as the consequence of carbon dioxide emissions (CO_2), which occur when slurry is exposed to atmosphere, like in a slurry tank or lagoon. In stored slurry, the pH within 1 mm below the surface may be significantly different than the pH measured in the deep layers (Canh *et al.*, 1998). In this model the difference in pH from bulk to surface slurries has been fixed to 0.6 unit of pH respect to the initial pH value. Indeed the effect of pH is moderated by CO_2 emission, which declines as pH increase (Blanes and Vidal 2011; Hafner *et al.*, 2013). Ka is usually calculated from the constant of dissociation in water (Kd). In literature, a number of values can be found for Kd and Kh (Henry's constant), parameters crucial in NH_3 volatilization models (Montes, 2009). Arogo *et al.* (2003) reported that the constant of dissociation (Ka) for liquid slurry was about 50% of the Kd in deionised water at 25 °C. Zhang (1994) reported that the constant of dissociation in diluted finishing manure (1% solid content) was one fifth ($1.143\ 10^{-10}$) the magnitude compared with Kd of NH_3 in water at room temperature. For a modelling approach Kd and Ka need to be chosen among literature sources (Clegg and Brimblecombe, 1989; Montes, 2009). The Henry's constant relates the concentration of dissolved NH_3 in water or manure to an equilibrium concentration of the NH_3 in the air space immediately above the liquid surface. Kh is less variable than Kd, so its value is generally assumed for pure aqueous solutions (Clegg and Brimblecombe, 1989):

$$\mathrm{Kh} = \exp\left(-8.097 + \frac{3917}{\mathrm{T}} - 0.00314 * \mathrm{T}\right) \qquad \text{(eq.3)}$$

According to Montes (2009), Kd, the constant of dissociation of ammonia in pure aqueous solution, is a function of absolute temperature and of chemical equilibrium between ammonia and ammonium. It depends on pH and temperature, and it could be modified with an empirical factor (E). Slurry is a moderately concentrated solution with pH largely controlled by NH_3 and CO_2 (Hafner and Bisogni, 2009). In extrapolating results from slurry, it has been assumed that the organic matter adsorbs some of the ammonium and ammonia in solution. However, several modellers have not considered that manure has different characteristics respect to an aqueous solution.

$$\mathrm{NH_4^+(aq) + H_2O(l) \rightleftharpoons NH_3(aq) + H_3O^+(aq)} \qquad \text{(eq.4)}$$

$$\mathrm{Kd} = 10^{0.05-\frac{2788}{\mathrm{T}}} \qquad \text{(eq.5)}$$

$$\mathrm{Ka} = \mathrm{E} * \mathrm{Kd} \qquad \text{(eq.6)}$$

This misunderstanding has led to models with overestimation of ammonia volatilization (Genermont and Cellier, 1997). Arogo *et al.* (2003) suggested an empirical factor between 0.50 and 0.94, based on the temperature of the slurry solution. According to Genermont (1997), who referred an overestimation in ammonia emission around 25%, using only Kd, for this model it has been chosen a value of 0.76 for the empirical factor (E) in order to obtain Ka. Assessed NH_{3gas}, the ammonia volatilization has been calculated via resistances approach. The traditional resistances approach is explained by the following equation (Olesen and Sommer, 1993):

$$\mathrm{hm} = 1/(\mathrm{Ra} + \mathrm{Rb} + \mathrm{Rc}) \qquad \text{(eq.7)}$$

Where Ra is resistance in the turbulent layer above the slurry; Rb is resistance in the laminar boundary layer between the gas-liquid interface and the turbulent layer; Rc is the resistance of the slurry cover.

Rc, dependent on slurry surface properties, has been estimated for a slurry surface exposed directly to atmosphere or a covered surface. Thus in this model Rc was considered the only crucial factor that modifies the Montes equation (2009). Indeed the mass transfer coefficient (hm) could be found also with this expression:

$$\mathrm{hm} = 0.000612 * \mathrm{U}^{0.8} * \mathrm{T}^{0.382} * \mathrm{l}^{-0.2} \quad \text{(eq.8)}$$

where U is the wind speed, T is the temperature, l is the length of the patch.

The length of the patch has been obtained as a function of the area of storage, which can be calculated with the module of slurry production. The mass transfer coefficient (hm) is affected mainly by wind speed, surface roughness and temperature (Raichpal-Sing and Nye, 1986). Ra and Rb are parameters related to the atmosphere, and included implicitly in Montes equation. Furthermore, Rc is generally the largest of the three resistance terms. This resistance is considered as a coefficient that gives 1 for no cover, and minor values for different type of covers and thickness of crust (Sommer, 2013):

$$\mathrm{hm} = \mathrm{Rc} * 0.000612 * \mathrm{U}^{0.8} * \mathrm{T}^{0.382} * \mathrm{l}^{-0.2} \quad \text{(eq.9)}$$

Following this approach, it has been hypothesized that in case of frost, which is induced by temperature equal or below zero, no emission of ammonia occurs.

Table 1: Values for Rc found in literature, from Sommer 2013

Cover	**Rc (coefficient of reduction)**
No cover	1
Straw	0.8
Oil	0.7
Natural crust	0.5
Clay granules	0.12
PVC sheet	0.11

Finally, the overall ammonia emission can be calculated as:

$$\mathrm{Emi}NH_3 = \mathrm{F}NH_3 * \mathrm{AreaStorage} \qquad \text{(eq.10)}$$

2.2 The module of manure production

This part of the model is useful to determine TAN concentration in slurry, a crucial parameter that deeply influences ammonia emission. According to Provolo (2010), the amount of slurry produced by livestock could vary significantly, due to different manure management techniques. The sub-model of manure production adopts relationships that link animal type to the production of excreta. The daily production of excreta (ExcP) is a physiological response of the animal, represented by Pedersen equation, which considers the manure production as an excreta addiction with a delay respect to metabolic activity.

$$\mathrm{ExcP} = \mathrm{Nani} * \mathrm{Kt} * \left(1 + 0.45 \left[\sin\frac{2\ \pi}{24} * (\mathrm{Time} - 8.75)\right]\right) \qquad \text{(eq.11)}$$

Where Nani is the number of pigs; Kt is the daily rate of manure per animal and corresponds to a percentage of animal weight.

Nani and Kt are parameters related to different types of animals, and selectable by the model users. For fattening pigs, it has been assumed a daily rate of excreta correspondent to 10% of animal weight. The final value of excreta production (ExcP) is then corrected by the management techniques, in order to get the filling of storage and their concentration of TAN. It has been considered an equivalent transformation from excreta to slurry because slurry density doesn't differ significantly from water density (Yague *et al.*, 2012).

$$\mathrm{Slu} = \mathrm{ExcP} * \mathrm{DilF} \qquad \text{(eq.12)}$$

where Slu is the slurry in storage, and Dilf the dilution factor

The dilution factors are dependent on the farm management, and the higher values generally correspond to a waste of water in the animal house.

Table 2: Average slurry production for a fattening pig under different farming practices

Management	Max value	Solid floor	Partially slatted floor	Fully slatted floor
Dilution factor	2.5	2	1.5	1.1

The concentration of TAN could vary significantly, depending on the manure management systems. For TAN in slurry, it is possible to calculate the concentration using the manure production module equations or simply taking values from literature. The first option should be very useful for farmers, to apply the model at a real scale; the second option allows to study the behavior of the model in different scenarios. Using dilution factors is possible to calculate the state of filling for storages, and the TAN concentration in lagoons and tanks. Another assumption of this model, frequently used in similar studies (Misselbrook *et al.*, 2000), is that slurry storage systems always contain some waste, and so they will emit NH_3 for the whole year.

2.3 Simulation experiments

Data on slurry chemistry, manure management and weather conditions are required to work with the model. Meteorological data used for these simulations are considered representative for Po Valley and Denmark and have been chosen from the Danish and Italian weather stations of Silkeborg and Capralba.

Table 3: Meteorological datasets used for simulations

Location	Latitude longitude	Year	Temperature (C°)	Precipitation (mm/year)	Wind speed (m/s)
Silkeborg (DK)	56° 11′ 0″ N 9° 33′ 0″ E	2011	8.94	984.4	3.84
Capralba (IT)	45° 27′ 0″ N 9° 39′ 0″ E	2011	13.52	981.2	1.86

The model works with hourly values of temperature, precipitation and wind speed. Denmark has a mean annual temperature around 8 °C and Po Valley, where the majority of Italian livestock is concentrated, is a quite climatic homogeneous area with a mean annual temperature around 13 °C. Farms with 1000 fattening pigs per year were taken as standard denominators for a comparison of ammonia emissions from livestock production in Italy and Denmark. The characteristics of slurries from these pig farms are resumed hereinafter.

Table 4: Composition of pig slurries used for modelling ammonia emissions in our experiments

Weather station	Storage	Area (m^2)	Bulk pH	TAN ($g\ L^{-1}$)
Capralba	Lagoon	1224	7.2	2.6
Capralba	Lagoon	1224	7.4	2.8
Capralba	Lagoon	1224	7.6	3
Capralba	Tank	840	7.2	2.6
Capralba	Tank	840	7.4	2.8
Capralba	Tank	840	7.6	3
Silkeborg	Tank	840	7.2	2.6
Silkeborg	Tank	840	7.4	2.8
Silkeborg	Tank	840	7.6	3

3. Results and Discussion

A sensitivity analysis has been performed to identify crucial parameters for ammonia volatilization. The storage system is conditioned by two chemical parameters (pH and TAN) and one physical parameter (volume of storage). The parameter concerning the chemical correction of surface pH (Cor) should not be used by model users, but only modified by scientists if they assume another value.

Table 5: Results of sensitivity analysis

parameters	Obs	mean	st. dev	min	max
pH	8760	16.66	0.19	15.81	16.90
Ta *	8760	1.00	$1.95E^{-4}$	0.10	1.00

*Ta is TAN, Total Ammonia Nitrogen

The manure management technologies have influences on the size of storages, and the surface exposed is proportional to ammonia emission. As a consequence, Italian lagoon has emitted for the reference year an higher amount of ammonia respect to Italian and Danish tanks. Using Italian meteorological data, and comparing farms with the same management and consistence of pigs, simulations indicate an increase in emitting surface around 38 % when lagoon is preferred to tank as storage structure. Regarding the ammonia emission, three experiments have been performed and compared with data from uncovered slurries.

Table 6: Results of ammonia emission from Denmark and Italy

Experiment	Danish Tank ($g\ m^{-2}\ day^{-1}$)	Italian Tank ($g\ m^{-2}\ day^{-1}$)	Italian Lagoon ($g\ m^{-2}\ day^{-1}$)
1 (pH 7.2; TAN 2.6)	0.714	1.255	1.205
2 (pH 7.4; TAN 2.8)	1.209	2.11	2.026
3 (pH 7.6; TAN 3)	2.029	3.5	3.361

The experiments have shown an high variability in ammonia emissions, dependent on chemical characteristics on slurry, temperature and wind speed. For the Italian tank the proposed model has simulated a mean of 2.242 g m^{-2} day^{-1}, for the Italian Lagoon 2.197 g m^{-2} day^{-1}, for the Danish Tank 1.317 g m^{-2} day^{-1}. However the very small decrease in emission per square meter of lagoon respect to Tank cannot balance the global ammonia emission from the lagoon larger surface. Temperature has a great influence over the process, with emission fifteen times higher in summer (Italy) and eight times in Danish summer. This is caused by peaks in hot summer, because temperature has more than proportional influence on ammonia emissions. As shown in other studies, temperature has a great influence on ammonia emission: the nitrogen loss in Italy is 69% more than in Denmark, where there are windy condition (mean 3.84 m/s). For the whole year, the nitrogen losses in atmosphere via ammonia emission is equal to 5.32% for Silkeborg and 9.01% for Capralba. The model shows a great sensitivity to parameters pH, TAN, and the direct exposition of slurry to the atmosphere. For this reason covering slurries should be a mandatory measure for Italian storages, as required by the Denmark law. The opportunity to simulate slurry covers is an interesting option of the model, useful to forecast the emission of NH_3 from farms, but it works only with values taken from other studies, so it is considerable just a technical result. Another possible advancement in the Italian legislation should be the prohibition to build lagoon as a structure for slurry, because of the greater surface area respect to thank, which is crucial for the increase of ammonia losses (Nicholson, 2002). The adoption of fully slatted floor should be encouraged because this technique reduces water consumption and requires a smaller storage for the farm. Considering daily mean, the simulated values are coherent with a range of values found in literature (Hristov *et al.,* 2010).

4. Conclusion

The high density of livestock farms and people in these countries obliges to manage manure in an environmental friendly way. Due to the Italian meteorological conditions, the emissions from Italian husbandry should be limited by the adoption of a set of abatement strategies. The first is avoiding lagoon as a slurry storage, that is instead prohibited in the Danish law. After this, covers of slurries and the acidification should be encouraged. A number of models have been found in literature, but most of them are simply empirical, whereas others too demanding to be used by farmers. Instead the proposed model is easy to use, despite it is more complex than emission factors approach (eg. seasonal climatic variability is accounted), and moreover it provides values on hourly bases. The module of manure production is an advancement respect to these models, that do not allow to choose important parameters as animal mean weight and management techniques. The easy usability of this model suggest that Emission factors method is quite rough, not adequate for the calculation of ammonia emitted from storages, because a large number of factors have a clear influence on the emissions: technology, climate, the kind of animal kept, their weight, age and diet. These factors differ from Italy to Denmark. Even within countries, due to structural differences in agricultural, there may exist substantial differences in emission factors between regions (Hutchings *et al.*, 2001). Further development of this work will be the validation of the model under Mediterranean condition where, despite the importance of manure management, few studies have been done (Yague and Bosch-Serra, 2013).

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3. Nitrogen losses from slurry spreading in SRC

Most of the volume of animal manure produced in Europe is applied to fields as slurry (Menzi, 2002). The amount of emission is variable and dependent on a number of factors involved in ammonia volatilization process. Recently in this area of research Short Rotation Coppice crops have been collecting great interests, because of the opportunity to use slurry as a valuable fertilizer for bioenergetics purposes. The term SRC customarily refers to biomass production systems for energy purposes, using fast-growing tree species. They are high-density plantations of fast growing trees for rotations shorter than 15 years (McAlpine *et al.*, 1966; Herrick and Brown, 1967; Afas *et al.*, 2008). SRC are distinguished from Short Rotation Forestry that is harvested in longer intervals. The very SRC cultivation scheme has even a plant density higher than 5500 plants ha^{-1} and harvesting cycle of 1-4 years (Manzone *et al.*, 2014). Willow (Salix spp.) and poplar (Populus spp.) are the most used plants for SRC in Europe, and their use is projected to increase in the near future (Dimitriou *et al.*, 2011). Multiple environmental benefits have been investigated in these systems (Berndes *et al.*, 2008). Among these the nitrogen trapped to sustain yields, especially with the use of society's residues, such as wastewater, slurries, digestate, that permit to achieve both the environmental, energy and farmers goals. It is considered a strategy for facing nitrogen challenge using phytoremediation, a cost effective plant-based approach. Despite the importance of these studies, still little is known about the nutrient use and efficiency of poplar SRCs, and how they vary according to factors such as site conditions (Paris *et al.*, 2011) Management of intensive short rotational system in some cases have shown high productivity and it is also a promising crop option on marginal agricultural lands and waste disposal sites (Isebrands and Karnosky, 2001; Laureysens *et al.*, 2004).

Short rotation coppice crops (SRCcrops) are recommended to provide renewable energy (Balasus *et al.*, 2012). In this work the initial stage and mature stage of SRC crops, and their response to organic fertilization, have been studied. Using slurry as an organic fertilizer in short rotation woody crops could be an interesting measure, but a number of aspects should be taken into account before to get a positive global assessment: excessive amounts of fertilizers can negative affect site carbon budgets (Crutzen *et al.*, 2007) and economic efficiency, exacerbates weed competition in the early stage of plantation and lower biomass production. On the other side, an adequate fertilization in SRC crops enhances productivity, mitigates the impact of severe drought, and it is an efficient way to dispose of manure. Considering the negative and positive effects of organic fertilization in such agro-systems is suggested to perform a nitrogen balance in order to consider the trade-off of fertilization. The nitrogen dynamics in the initial stage of the plantation have found place in a publication sent to Agriculture Ecosystems and Environment, whilst data on the mature stage of short rotation crops have been collected and will be used for a new publication. During these years two sites have been investigated, the first in Tezze sul brenta, where a Plane plantation has been established in the spring of 2009, and the second in Monastier, where Poplars have been established in the spring of 2013. The experiments conducted in mature short rotation coppice plantation have been the core of the second paragraph of this chapter. In the two sites of Tezze sul Brenta and Monastier, Plane and Poplar plantations have been monitored in their nitrogen dynamics, with a specific regard to ammonia emissions, the most important pollutant that comes from the distribution of fertilizers on agricultural land.

Emissions associated with spreading can vary from 0 to 60% of the applied ammoniacal nitrogen (Bussink *et al.*,1994). A common observation in experiments is that the trend in ammonia emission from fields follows the Michaelis-Menten equation.

$$N(t) = Nmax\ (\frac{t}{t + Km})$$

where N(t) is the cumulative loss fraction of TAN; Nmax is the total time integrated loss; Km the time when half of the total emission occurred.

The instantaneous emission rate corresponds to the derivative dN/d t of the above equation:

$$dN\ dt = Nmax\ Km\ (t + \frac{Km}{2})$$

Ammonia emissions following distribution of slurry in the field is an important source of pollution, and also represents a valuable loss of nitrogen in fertilization. Over time, the emission of NH_3 from slurry spreading can be considered as a two steps process (Sommer *et al.*, 2003). The first step lasts from the time of application until the infiltration of slurry into soil is complete, and the second lasts from infiltration until when the NH_3 emissions become negligible. It is possible to simplify and consider the emission of NH_3 from slurry applied to field dependent on evaporation and infiltration of slurry. Ammonia losses following field application, and then the amount of nitrogen that enters into the soil nitrogen cycle, dependent on climate and crop height (Thorman *et al.*, 2008). Climate is characterized by environmental variables as rainfall, wind speed and temperature. Rainfall before manure application affects the soil moisture content and may dilute the manure or decrease infiltration of the manure into the soil. If it occurs directly after slurry application improves infiltration into the soil, and decreases ammonia volatilization (Freney *et al.*,1983). Rainfall also decreases evaporation and, in this way, indirectly decreases volatilization. Irrigation after slurry application may, similar to rainfall, improve infiltration (Mulder and Huijsmans, 1990). Clearly soil water content is related to precipitation and irrigation, and it has been shown that wet soils have an higher potential for ammonia volatilization (Søgaard *et al.*, 2002). According to Montes (2009), the transfer coefficient of ammonia can be estimated as a function of temperature, wind speed and the length of the emitting surface. Losses of NH_3 from surface where urea has been applied generally increase in windy conditions (Vaddella *et al.*, 2013). Since windy condition and drying soils are often related, both of these factors tend to aggravate the potential for ammonia volatilization. Ammonia losses increase with rising temperature due to the effects on both chemical and biochemical reactions: Søgaard *et al.* (2002) reported an increase of TAN volatilized around 2% per increase of Celsius degree. The presence of crops is an advantageous measure to reduce ammonia emissions, due to the shadowing of slurry, the decrease of wind speed within the crop (Denmead *et al.*, 1982) and the gaseous ammonia uptake by vegetation (Sommer, 1993). The role of vegetation in absorbing NH_3 is well known: ammonia is transported into the leaf via stomata (Van Hove *et al.*, 1987). The field size is another important aspect: the flux of ammonia from soil to the free atmosphere is two-dimensional, so the horizontal flux as well as the vertical flux should be included in process considerations (Loubet *et al.*, 2001). Increasing the area where slurry is distributed reduces the “border effect”, which is related to an increase of the gradient of concentration between soil and atmosphere. Soil chemistry (CEC) is another factor that influences ammonia volatilization, contributing to the immobilization of nitrogen compounds in soil (Sommer *et al.*, 2003). Furthermore the applied TAN may be depleted by microorganism thorough transformation to nitrate or ammonium. The rate of transformations by microorganism depends on many factors, such as the population of microorganisms, the soil temperature, water and oxygen concentrations, and the inhibition that occurs under high TAN concentrations (Morvan *et al.*, 1997). Other factors beyond the environment have an influence on the process of volatilization from fields. The volatilization has been shown to be significantly and directly correlated to dry matter content (DM). Sommer (2003) identified slurry DM as a factor influencing infiltration of slurry into soil, Huijsmans (2003) summarized that slurries with higher TAN contents are normally associated with higher ammonia emissions, and that there is a good correlation between concentrations of ammonia and TAN in slurry. Since slurries with lower DM contents often contain lower TAN contents, the total ammonia emissions are reduced. The pH of slurry has an essential role on the emission of NH_3, and it is controlled by a number of acids and bases, of which the most important are volatile fatty acids (VFA), total inorganic carbon (TIC) and total ammonia nitrogen (TAN) (Sommer and Husted, 1995). Basically, volatilization of NH_3 will decrease pH, and volatilization of CO_2 will increase pH. Because the solubility of CO_2 is around 200 times lower than that of NH_3 (Beutier and Renon, 1978), a pH increase around one unit frequently happened after slurry application, and it lasts for some hours, contributing to an increase of ammonia volatilization. After a period of 24 -24 hours, the pH at the soil surface decreases due to the buffering capacity of soil and slurry (Sommer *et al*., 1991).

3.1 Nitrogen emission from juvenile short rotation coppice crops

Publication prepared for Agriculture Ecosytem&Environment Journal

Organic fertilization and N dynamics during the initial stage of *Platanus hispanica* in short rotation forestry

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Highlights

N dynamics in a forest infiltration area and in a permanent meadow were studied.

N balance collecting measurements on N losses (groundwater leaching and gaseous emission) in these environments were performed.

Keywords

Short Rotation Forestry; Forested Infiltration Area; organic fertilization; leaching; emissions; N balance.

Abstract

Bioenergy crops are a promising option for integrating fossil fuels and achieving European environmental targets. Among these, Short Rotation Forestry (SRF) crops have been considered an opportunity for sustainable agricultural development, because of the environmental benefits related to their use on agricultural lands. At present, little is known about several implications related to the adoption of SRF crops, mainly the effect of fertilizers on biomass yields and the amount of N losses (leaching towards water bodies and gas emission). In this case study, a SRF plane plantation has been grown in a Forested Infiltration Area (FIA) to prove the paths of distributed reactive nitrogen (N) in this agricultural system. For this purpose, a N balance has been performed by comparing a permanent meadow to the SRF *Platanus hispanica* plantation, using two different amount of organic fertilization (digestate) for each system (170 and 340 kg N ha^{-1} $year^{-1}$). The results obtained during the first year show that in presence of high permeable soils, the FIA is not effective in retaining N during the initial stage of growing and its potential in removing N does not vary linearly with the applied dose of digestate. Consequently, the adoption of SRF in FIA systems is suggested only if the fertilization is not high during the initial stage of plantation, otherwise high leaching rates in groundwater might occur.

1 Introduction

To face increasing environmental problems such as the competition for energy resources and global climate change, alternatives to limited fossil energy resources are required. Short Rotation Forestry (SRF) crops, among energy crops, are recommended to provide renewable energy (Scholz *et al.*, 2008). SRF refers to single or multi-stemmed trees of fast growing species, grown on a reduced rotation length primarily for the production of biomass. SRF biomass is treated by the European Commission (EC) as a conventional agricultural product. Nowadays, there is a global rising interest for woody biomass that is considered more convenient, with respect to other renewable energy sources (Hauk *et al.*, 2014). Besides substituting fossil fuels, SRF crops provide environmental advantages, such as reduced wind and water erosion, carbon sequestration in the soil by reduced soil cultivation, accumulation of organic matter (OM) and possibility of phytoremediation (Grogan and Matthews, 2001). The recent policies enacted by the European Union (EU) foresee an increased interest in the cultivation of energy crops. The EC prescribes an increase in renewable energy generation, of which biomass currently contributes 66% (European Commission, 2014). Woody biomass has been financed by the European Agricultural Fund for Rural Development, in order to reach sustainability targets within 2020. The adoption of SRF crops can be seen as a core point in the European policy on agriculture (2014-2020), as a consequence of the new regulation UE n. 1310 (2013). The first pillar of the Common Agricultural Policy (CAP) (43.45 billion euro) concerns the income support, which is an economic aid that must be associated with seven specific duties for farmers. Among these, greening is really important because 30% of the first pillar financial fund is bound to services concerning ecological conservation and measures to face climate change. SRF and Forested Infiltration Area (FIA) according to regulation should occupy at least 5% of the farm land, in order to satisfy the greening point. The second pillar of CAP (13.82 billion euro) regards the policy for rural development, that can be integrated with the first pillar. SRF and FIA are considered a step towards a carbon-free agriculture, and 30% of the second pillar financial funds will be allotted for some environmental measures, among these soil protection and strategies to face climate change (European Commission, 2015). Farmers usually grow short rotation crops on land with insufficient nutrient and water supplies for annual crops (Balasus *et al.*, 2012). In fact, the use of mineral fertilizers in SRF is generally neglected because it is uneconomic (Balasus *et al.*, 2012). However, farmers have interest in increasing yields of cultivated energy crops, possibly recycling inexpensive resources, for example digestate and other slurries, as suggested by sustainable agriculture principles. For this study, a FIA (Mezzalira *et al.*, 2014) has been cultivated with SRF plants, with the aim to study the effect of organic fertilization on these agricultural lands. Slurry is considered a valuable and unexpensive fertilizer, but the geographical concentration of livestock in areas with little or no agricultural lands has led to manure management worries (Oenema *et al.*, 2007). Slurry contains N, P, K and other microelements that sustain crop growth. However, it could be also a source of organic and inorganic pollutants (Nicholson *et al.*, 2003; Puckett, 1995). The role of organic and chemical fertilization in eutrophication of surface waters (de Jonge et al., 2002), acidification of soils (Sutton *et al.*, 2011) and nitrate (NO_3^-) leaching are well known (Kramer *et al.*, 2006). Another key issue is the atmospheric pollution related to slurry spreading on cultivated land, that causes ammonia (NH_3) volatilization and nitrous oxide (N_2O) emissions (Sommer *et al.*, 2004). The Gothenburg Protocol and European directives have the aims of limiting such emissions. Considering these environmental worries, the recycle of organic waste in SRF could be an interesting option to improve soil fertility, provide nutrients for crops, and recycle sewage waste (Dimitriou *et al.*, 2011). In the present case study this has been achieved using digested slurry with an high fertilization value (Moller and Stinner, 2009). The EU has encouraged the use of biogas to produce energy, and consequently there is a need of recycling digestate as fertilizer with high content of inorganic N. Even though biomass is a key energy carrier with a good potential for on-farm development, little is known about N fertilization effects on SRF; few studies have been conducted on this topic, especially on the first and second year of SRF planted with cuttings (Balasus *et al.*, 2012). Although the economic impact of SRF crops have been deeply investigated, comprehensive assessments of nutrient cycling in bioenergy crops plantations are rare. There is a need for research to identify possible soil and plant responses to organic fertilization in a range of site conditions (Quaye and Volk, 2011). Slurry spreading in the early stage could lead to high leaching rates (Balasus *et al.*, 2012) and high NH_3 volatilization rates, due to a scarce cover of soil. Coleman (2004) found an effect of organic fertilization on low doses (50 kg N ha^{-1} $year^{-1}$) while for greater amount (100 to 150 kg N ha^{-1} $year^{-1}$) no additional growth in poplars was observed. Hytönen (1995) states that N fertilization seems to be necessary for the growth of willow. Adegbidi *et al.* (2001) underline that the use of organic waste (adequately chosen with regard to known nutrient deficiencies) as a soil amendment in bioenergy plantations could supply needed nutrients, while reducing the cost of production. In general, concerning manure management studies, NH_3 volatilization in Mediterranean environments should be better studied (Yagüe *et al.*, 2011). There is no global standard method to detect NH_3 emission, which is the main gas emitted from slurry spreading, and each method can give different values of NH_3 emission for the same condition (Søgaard *et al.*, 2002). In literature, there is no information about SRF on Plane, an energy crop used in Italy (Facciotto *et al.*, 2009). These diverse questions emerging from literature are crucial for this study. The aim of this explanatory research has been the assessment of N dynamics in an SRF plantation with Plane (*Platanus hispanica*) located in the Brenta basin (Tezze sul Brenta, VI), in order to investigate if FIA are suitable for slurry spreading, and the estimation of the impact of organic fertilization on biomass production. The area of the Brenta basin is characterized by an intensive animal husbandry and high load of N on agricultural fields, for this reason most of the territory has been classified as Nitrate Vulnerable Zone (NVZ), as required by the NO_3^- directive. This area, unlike others defined as NVZ, is indeed vulnerable because of the quite fast dynamics of soil hydrology, being located in a huge alluvial fan (Fontana *et al.*, 2008; Mastrocicco *et al.*, 2015). Hence, in the Brenta basin, measures to efficiently recycle N are needed and thus in this case study one of these measures has been applied. This study aims at proving whether and to what extent SRF crops reduce the risks of N pollution caused by organic fertilization in no conservative soils. A N balance has been performed in order to assess the sustainability of organic fertilization on SRF plantations. The best result for a N balance should be minimum losses in leaching and emission, the preservation of soil fertility, and a balancing overall result. For this purpose, NH_3 volatilization, N_2O emissions and NO_3^- leaching have been investigated, doing a comparison with a traditional agricultural system consisting of a permanent meadow adjacent to the SRF plantation.

2. Material and Methods

2.1 Experimental site setup and soil condition

The experimental site, located in Tezze sul Brenta (Vicenza, Italy 45°41'00"N and 11°42'00"E), is characterized by a loamy gravel soil, classified as Typic Hapludalfs loamy-skeletal, mixed, mesic soil according to the USDA classification (1999). At the start of the experimental campaign, the soil was characterized by a high N content, probably as a consequence of former maize cultivation, with high loads of N distributed per year. The groundwater level fluctuates approximately between -15 and -19 m below ground level (b.g.l.) (Mastrocicco *et al.*, 2015). The area is located North of the spring belt (Fontana *et al.*, 2008), in the main recharge area of the Venice lagoon drainage basin. The soils are characterized by a quite fast infiltration rate, but the presence of significant content of fine sediment (silt and clay) in the first 45 cm layer leads to a delay in percolation time. In table 1 the main characteristics of the soil are resumed. Unless otherwise specified the experimental period was from January 2010 to September 2011, while the annual N balance has been performed in the period between May 10, 2010 and May 9, 2011. For the chemical analysis of soil, the extractions have been carried out using K_2SO_4. The total N and P were determined by spectrophotometric analysis after oxidation. Bulk density was determined using the method proposed by Blake and Hartge (1986). Soil pH was determined electrometrically in the supernatant after shaking 5 g of soil with 25 ml H_2O at field moisture for 1 h. The climate of the area is temperate according to the FAO classification (1999), and is characterized by cold winters and hot summers, moderate precipitations, high relative humidity, low wind speed, moderate daily and seasonal temperature excursions, with mean annual precipitation of 1180 mm and mean temperature of 13.5 °C. The FIA was realized in spring 2009, in a field formerly cultivated with maize. The infiltration of surface water has been guaranteed by a system of parallel ditches in connection with the existing irrigation net. The FIA has a surface of 3000 m^2 (49×60 m), in which *Platanus hispanica* Mill ex Muench, a hybrid of *Platanus orientalis* x *Platanus* *occidentalis*, was planted with a distance between rows of 2.5 m and a distance within of 2.0 m. A permanent meadow field has been chosen for the comparison with *Platanus hispanica*. Measurements on N losses have been done over six thesis, as described in Figure 1.

Fig. 1 Experimental design

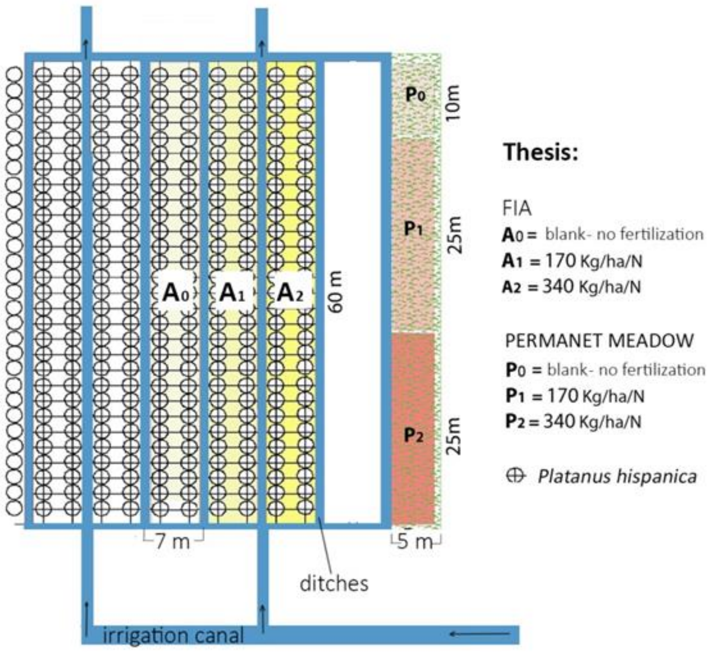


Table 1: Physical-chemical features of the soil at the experimental field.

Soil Horizons	O	A	B	C
Horizon depth (cm)	0 - 35	35 - 45	45 - 75	75 - 120
Gravel (%)	20.0	55.0	55.0	60.0
Sand (%)	55.3	69.2	82.9	88.1
Silt (%)	30.7	22.6	9.9	8.7
Clay (%)	14.0	8.2	7.2	3.2
pH	7.1	7.6	8.0	8.9
$CaCO_3$ (%)	<0,5	<0,5	6	46
Organic Carbon (%)	2.0	0.4	0.2	0.1
P (mg kg^{-1})	100	*	*	*
CSC (meq $100g^{-1}$)	17.0	9.8	5.9	2.7
Hydraulic conductivity	slightly high	slightly high	high	high
Bulk density	1.26	1.39	1.30	1.51

During the experimental campaign, three spreading events with slurry from biogas plant (digestate) have been performed, as reported in table 2. For the A1 and A2 thesis, the fertilizations have been done using the trailing shoes technique, which includes a tillage, whereas in P1 and P2 thesis the fertilizations have been performed through the conventional broad-spreading.

The chemical and physical characteristics of the digestate were analyzed before each spreading event, and are presented in table 3.

Table 2: Fertilization events during the experimental period.

	A1		A2		P1		P2	
Date	Volume (m^3 ha^{-1})	N (kg ha^{-1})	Volume (m^3 ha^{-1})	N (kg ha^{-1})	Volume (m^3 ha^{-1})	N (kg ha^{-1})	Volume (m^3 ha^{-1})	N (kg ha^{-1})
11 May 2010	15.2	45.8	23.8	71.4	18.8	56.3	37.5	112.5
29 June 2010	22.8	72	45.8	144	19	59.9	37.8	118.9
18 October 2010	21.4	45.4	46	97.6	19	40.3	37.8	80
Total annual	59.4	163.2	115.6	313	56.8	156.5	113.1	311.4

Table 3: Main chemical characteristics of digestates used during the experimental fertilizations.

Date	TS (%)	VS (% TS)	Total N (mg l^{-1})	TAN (mg l^{-1})	Cl^- (mg l^{-1})	pH (-)
11 May 2010	5.4	672	3000	2300	*nd*	8.1 ± 0.2
29 June 2010	5.2	64.6	3150	1700	*nd*	8.4 ± 0.2
18 October 2010	2.7	62.1	2120	1203	500	8.2 ± 0.2

2.2 Soil moisture

The soil water content, expressed as % of volumetric water, was recorded every 30 minutes through FDR Probes (Frequency Domain Reflectometry, spectrum SM 100 waterscout soil moisture sensor) connected to a data logger (data-logging WatchDog 1000 Series Spectrum Technologies) and placed at different soil depths (15, 30, 60 and 90 cm b.g.l.). The soil moisture system was placed both in FIA and in the permanent meadow.

2.3 Soil N content

The mineral concentration of N in the soil was measured in correspondence of 12 different phases during the experimental period, at a depth of 0-30 cm, 30-50 cm, 50-80 cm, 80-90 cm in three different points (replicates) for each thesis. Each soil sample was further analyzed for soil moisture and total N (N_{tot}). Soil moisture was determined gravimetrically after drying subsamples at 105 °C for 24 h. Dissolved N_{tot} was determined with 2M KCl extraction followed by the persulphate oxidation method (Valderrama, 1981).

To calculate the soil N content (N_s) in different moments, the total biomass was calculated for each layer (according to the bulk density) and multiplied for the N_{tot} concentration values.

2.4 N contents of vegetation biomass and its yield

The assessment of woody biomass has been taken on 26 July 2011, with sampling and check weighing of young trees, and adopting mainly dendrometric relationships (De Pretto, 1999). For shoots greater than or equal to 3 cm, the double entry table was used (De Pretto, 1999). This method was used also for shoots from 2 to 3 cm of diameter, at least 4 meters high. This extension was considered adequate for a full chipping system. The used formula was:

$$Y = B_0 + B_1 X_2H + B_2H$$

Where:

Y = total weight (*kg*) of a single shoot

X = diameter (c*m*) at 1,30 cm

H = shoot height (*m*)

B_0, B_1, B_2 = numeric coefficients of the regression, calculated as 5.9627, 0.080 and 0…., respectively

The woody samples have been dried and weighted, and their N content was assessed by UNI CEN/TS 15104/2005 method. In addition, during the experimental campaign measurements have been done on three sampling areas of 1 m^2 for each thesis throughout the fall leaf period in order to assess the herbaceous and litter biomass; the collection times were of about 15 days. During August 2010, in FIA, a mowing has been performed to quantify the biomass of a weed (*Amaranthus sp.*) that was proliferating between the tree rows. The vegetation samples have been dried and weighted, and their N content was assessed by UNI CEN/TS 15104/2005 method. To calculate the vegetation N content, the measured biomass was multiplied for the N_{tot} concentration values.

2.5 N leaching

Reactive N species concentrations were measured on 26 samples taken during the period May 2010 - August 2011. The measurements have been taken at 30 cm, 60 cm and 90 cm b.g.l. using tension lysimeters. Tension lysimeters have a diameter of 63 mm and 60 unit of pressure (centibar). Especially during periods with low humidity of the soil, it was not possible to maintain the pressure in the suction lysimeters, and this caused the absence of some data in the 30 and 60 cm layers. On the other hand, at 90 cm, with rare exceptions, the samples were taken continuously. The $N\text{-}NO_3$ was measured by liquid chromatography (APAT CNR IRSA, Analytical Methods for Water, Method 4020, Manual 29, 2003). The $N\text{-}NO_2$ was measured by spectrophotometric analysis (APHA, AWWA, WEF, 1991 and APAT CNR IRSA, Analytical Methods for Water, Method 4050, Manual 29, 2003). The $N\text{-}NH_4$ was measured through spectrophotometry with Nessler reagent (EPA, 1979 - Method 350.2 and APAT CNR IRSA, Analytical Methods for Water, Method 4030 A2, Manual 29, 2003). The Total N was measured by spectrophotometric analysis after oxidation (Valderrama, 1991 and APAT CNR IRSA, Analytical Methods for Water, Method 4060, Manual 29, 2003). The volumes of water infiltrated have been estimated by applying the daily water balance method of Paniraghi and Panda (2003), considering the error in the assessment of actual daily evapotranspiration with the Penman-Monteith formula (Sumner and Jacobs, 2005), using soil parameters in order to calculate the actual daily infiltration towards the aquifer (Colombani *et al.*, 2015). The daily balance of N leached have been calculated by multiplying the daily volumes of water deep seepage (at 90 cm b.g.l.) by the concentration measured during the sampling date considered representative for that period.

2.6 Emissions of gases (NH_3 and N_2O)

Soil emissions of NH_3 and N_2O were measured in coincidence with the slurry spreading events. The measurement technique was based on the adoption of closed chambers (Conen and Smith, 1998), a method recommended to operate in heterogeneous conditions with adjacent thesis (Lovanh *et al.*, 2009; Misselbrook *et al.*, 2005). The volume of the chambers, made of plastic material (PVC) and of cylindrical shape, was 0.005072 m^3, with an height of 0.31 m and a surface area of 0.0109 m^2. The chambers were linked to gas monitors adopting PAS technology (Photo Acoustic Spectroscopy, Bruel & KjaerTM 1302) using Teflon tubes. The closed chamber, placed on the soil surface, detected the variation of NH_3 and N_2O inside the chamber at temporal intervals of 2 minutes; the chambers were left to stand on the soil from 12 to 20 minutes. NH_3 and N_2O emissions were consequently estimated calculating the slope of the regression line for the sampling points where the trend of gas is linearly increasing. During each experimental campaign these values, recorded at different hours after slurry spreading, were integrated in order to obtain the cumulative emission of NH_3 and N_2O per chamber. At least three measurements were taken for each spreading event, the first immediately after slurry spreading. Each experimental campaign lasted at least twenty hours, a time interval in which the majority of NH_3 is reasonably emitted (Gericke *et al.*, 2011).

2.7 Deposition

The rain volumes were measured in continuous by a WatchDog rain gauge data-logging 3554WD1-Spectrum Technologies attached to a self-emptying tipping bucket. The N_{tot} content in rain was measured by collecting every two weeks the water samples from a tank connected with the rain gauge. A balance of N deposition (N_r) was calculated by multiplying, for each period included between two samplings, the total volumes registered for that period by the measured N_{tot} concentration.

2.8 N balance

The N balance has been calculated as the difference between the N input in the systems (soil enrichment, fertilizations, rains) and its outputs (leaching, N content in woody and herbaceous biomass, emissions). The starting date (t_0) is May 10, 2010, while the end date (t_1) is May 9, 2011:

$$(N_f + N_r) - (N_L + N_{hb} + N_{wb} + N_e) = N_{den} + N_{err} + N_a$$

where:

N_f = N input by fertilizers (digested slurry)

N_r = N deposition by precipitation

N_L = N leaching at 90 cm b.g.l.

N_{hb} = N removed through mowing

N_{wb} = N sequestered from woody biomass

N_e = soil emissions of NH_3 and N_2O in coincidence with the slurry spreading events

N_{den} = N lost by denitrification during the period

N_{err} = unknown error: it is the sum of different sinks for N losses. It accounts for N uptake by leaves (Sommer *et al.*,1997), desynchronization of N dynamics caused by vegetation uptake (Hefting *et al.*, 2005), and the volatilization of NH_3 during the slurry distribution, from the spreading to the displacement of the chamber (Huijsmans *et al.*, 2001), and bacterial N_2 fixation (Balasus *et al.*, 2012).

N_a = N available for new processes (denitrification, leaching, uptake). N_a can't be distinguished from N_{den} and N_{err}, because denitrification was not measured continuously, even if, during five experimental campaigns soil samples at different depth (30, 60 and 90 cm) have been taken in order to measure in situ denitrification (DNT) by the static core acetylene inhibition method (Yoshinari & Knowles, 1976).

3. Results and discussions

3.1 Woody biomass

The total values of dry woody biomass estimated on July 26, 2011 ranged from 5.4 to 8.3 t ha^{-1} and clear differences between the thesis were recorded. Despite this, it was not possible to argue that digestate had a significant effect on the production of woody biomass, because the plant was still immature and the trees were in an adjustment stage, and the comparison between the thesis, performed via T student test, has not resulted significant. The differences of the total biomass most probably were overestimated because of the replacement of some damaged shoots, mainly in the A0 thesis. Table 4 shows the amount of N_{tot} stored in the woody biomass: two years after planting the values ranged from 19 to 26 kg N ha^{-1}. These values state a low uptake of N by trees plantation at this stage. On the contrary, some studies have reported significant values of immobilized N in woody biomass. As an example, Fortier *et al.* (2015) recorded values ranging from 110 to 300 kg ha^{-1} in a nine years poplar plantation.

Table 4: Total amount of N storage in the woody biomass two years after planting.

Thesis	A0	A1	A2
DM in woody biomass (t ha^{-1})	5.4	6.4	8.3
N content (kg ha^{-1})	19.9	18.6	25.7

3.2 Herbaceous biomass

The values of total dry herbaceous biomass recorded from May 2010 to May 2011 in all the thesis (Table 5) ranged from 6 to 13 t ha^{-1} $year^{-1}$. The biomass values showed clear differences between the two control thesis and the others fertilized with digestate and a clear and proportional effect of the fertilization has been demonstrated. These data are coherent with the literature, which reports an average annual production of approximately 9 t of hay per hectare in no irrigated meadows, mainly resulting from the first mowing, whereas in an irrigated one the production reaches an average of about 10-11 t ha^{-1} $year^{-1}$ (Paris *et al.*, 2011). In the three A thesis from 30 June 2010 to 23 August 2010 there was a significant growth of *Amaranthus sp.,* an invasive herbaceous specie. Unlike in the FIA system (thesis A0, A1 and A2), where only *Amaranthus sp.* was removed, the vegetation growth in the permanent meadow was completely removed after mowing. The mean N content in the herbaceous biomass was about 0.025 % and in *Amaranthus sp* was 0.02%. The total amount of N removed from the system was calculated taking into account this difference. On the other hand, the N content of herbaceous biomass left in the system was considered available N.

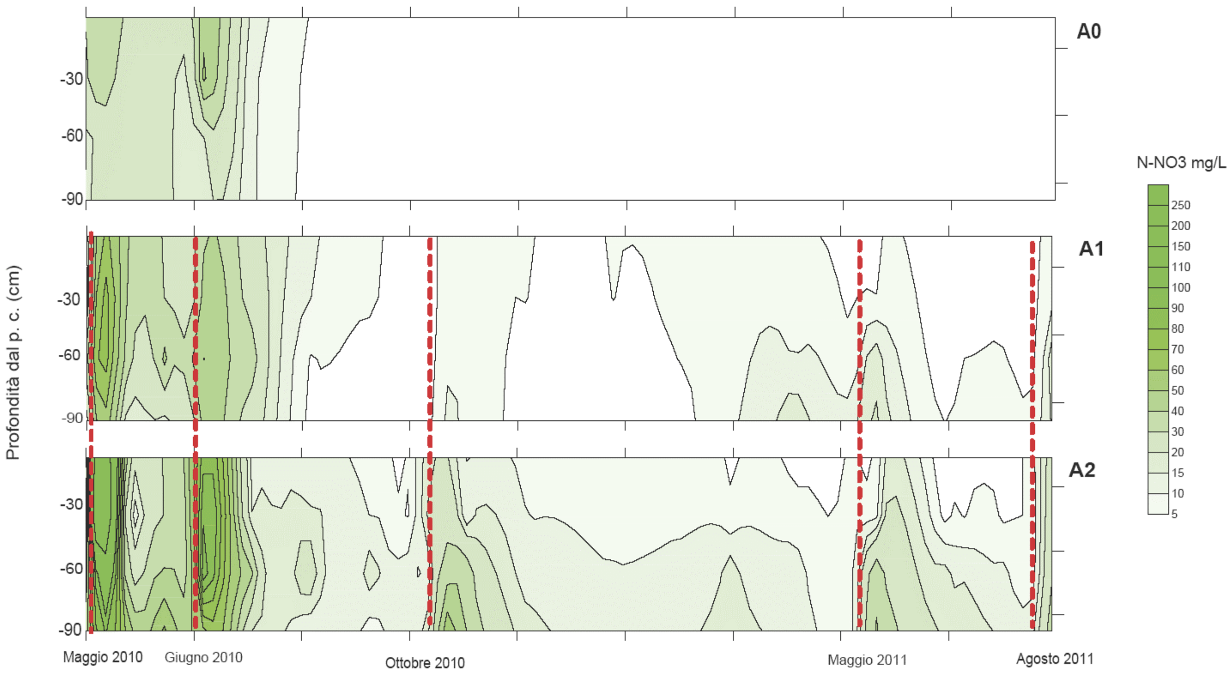
Table 5: N amounts in herbaceous biomass

	Dry herbaceous biomass (*t* ha^{-1} $year^{-1}$)	N available (*kg* ha^{-1} $year^{-1}$)	N removed (*kg* ha^{-1} $year^{-1}$)
A0	6	152	6
A1	9	218	24
A2	10	246	36
P0	8	0	188
P1	10	0	256
P2	13	0	340

3.3 N leaching

For each thesis, the concentration of $N\text{-}NO_3$ and N-tot recorded in the percolation water is shown in table 6. The $N\text{-}NO_3$ and N-tot concentration values are strictly proportional to the different input of digestate in each thesis for unit area. Data on $N\text{-}NH_4$ and $N\text{-}NO_2$ are not reported because they have values close to zero. The only exceptions are some peaks of $N\text{-}NH_4$ (10-15 mg/l) taken at 30 cm in P1 and P2 thesis, during 12 May 2010 and 26 October 2010 samplings, clearly associated to an incomplete nitrification in the digestate distributed during the previous days. In FIA, the high baseline value in A0 is probably due to the N residual from the previous activities, which influenced the first 3 months of the experimental activities as evident from the graph in figure 2.

Fig. 2 Distribution of the N-NO_3 concentration in the 0-90 cm soil horizon during the monitored period in FIA.



In the same figure it's evident that the dynamics and the time of permanence of N in the soil profile are rather fast and that the concentration tends to decrease in the first 2-3 months after each distribution, depending on the meteorological conditions during the study period. In term of mass balance the value of the N-tot leached is reported in table 7.

Table 6: Mean nitrate concentration in soil water at 90 cm b.g.l.

Thesis	A0	A1	A2	P0	P1	P2
N-NO_3 (*mg l^{-1}*)	6.43	14.50	29.72	1.42	6.86	13.31
N-tot (*mg l^{-1}*)	8.41	17.28	32.68	2.73	8.87	15.91

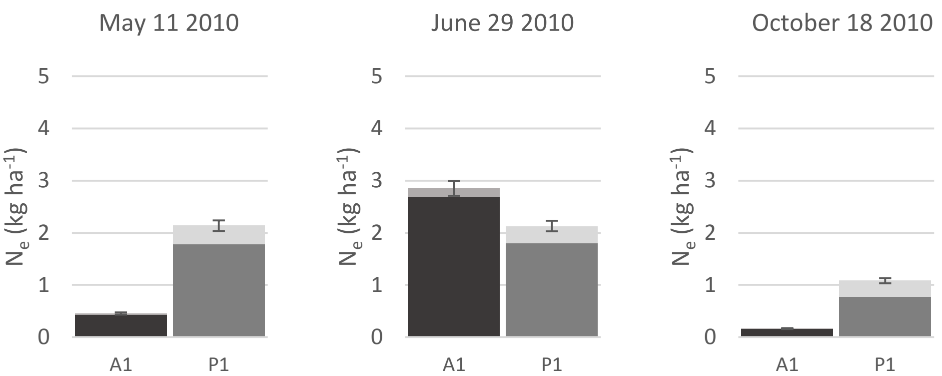
Table 7: Total leaching of N for each thesis.

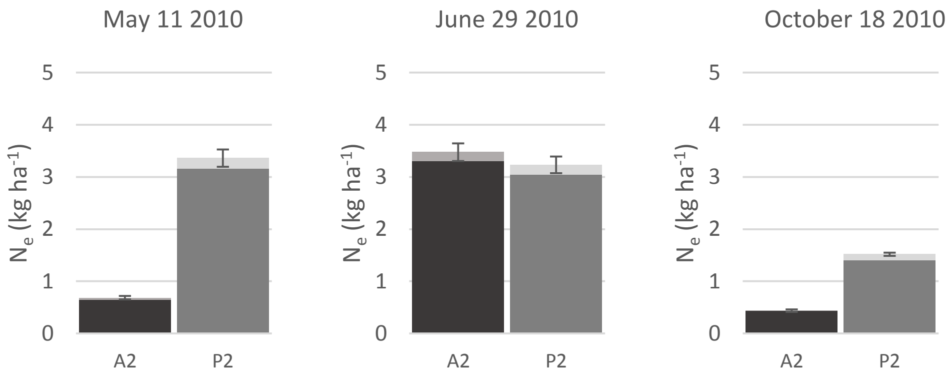
	Rainfall (*mm*)	Leaching at 90 cm (*mm*)	N-tot leaching ($kg\ ha^{-1}$)
A0	1603	564±113	35.21±2.76
A1			81.38±3.94
A2			111.24±7.56
P0	1603	536±107	14.82±0.59
P1			34.95±4.16
P2			82.88±7.82

3.4 N emissions

The global N emissions, in the case study, ranged between 4.6 and 11.4 kg ha^{-1} year^{-1}, which corresponded to 2.2 and 3.2% of the N distributed (figure 3).

Fig. 3: N emissions from the four thesis





Most of the N losses were in the form of NH_3. These emissions were in the range of literature, even though NH_3 emissions from slurry applied in the field were quite variable, ranging from 0 to 60% of the applied NH_3cal N (Bussink *et al.*, 1994). The emission of N_2O were low for all the thesis, ranging from 0.194 to 0.76 kg ha^{-1} year^{-1}, that corresponded to 0.2% of the total N distributed. As stated by FAO (2001), following the results of Eichner (1990) and Bouwman (1996), IPCC has proposed a default emission factor of 1.25% (defined as the percentage of the applied N that is emitted as N_2O) for all agricultural soils and all types of applied slurry (Mosier *et al.*, 1998). However, the low value of this assessment can be explained with the sampling time limited to 24 hours, whereas the assessment of IPCC considers a more extended period. The hot weather conditions that characterized the June experiments led to higher NH_3 emission for A1 and A2 thesis, as expected from the theory on NH_3 volatilization. Weather conditions, as well known from literature, have a crucial importance in determining N emission (Sommer *et al.*, 2003; Søgaard *et al.*, 2002). An higher emission level did not occur for P1 and P2 thesis because the bare soil in May led to a higher emission with respect to late June, where growing weeds had a shadowing effect that reduced emissions. Instead, in October, the low value of emission were probably caused by a combination of grassing between rows, cool temperature and cover of fallen leaves. The high variability in the presented data can be related with the variable chemical characteristics of the slurry (Tab. 3) , which have a great influence on NH_3 emissions, according to literature (Gericke *et al.*, 2012; Sommer and Hutchings, 2001). Regarding NH_3 emission, there is a direct relationship with pH and NH_3cal N

(Sommer *et al.*, 1991). The emissions from A1 and A2 thesis were proportional to the distributed slurry, and the ratio emitted-N on distributed-N could be considered equal. This result leads to the conclusion that the volume of distributed slurry is not a crucial parameter that influences NH_3 volatilization rate, but the extension of the spreading area is much more important, as shown in other studies (Huijsmans *et al.*, 2003; Sommer and Hutchings, 2001).

3.5 Atmospheric N deposition

The average N content in rain was equal to 2.1 mg /L. The annual rainfall between May 2010 and May 2011 was equal to 1603 mm. N inputs from the rain in the permanent meadow amounted to 33.7 kg ha^{-1} $year^{-1}$. Regarding the FIA thesis, the net contributions that fall directly into the area of interest can be accounted in 28.2 kg ha^{-1} $year^{-1}$ (differences are due to the rain fallen in ditches that do not affect the study system).

3.6 Inorganic N in soil

The comparison between the initial (May 2010) and final (May 2011) N content showed that there was a reduction in the N content in the soil (Table 8); this was due to the high percolation rate, and the high level of consumption of this element by the vegetation, in particular the herbaceous component, which demonstrated very high growth rates.

Table 8: Concentration of N in soil.

Depth	May 2010 (*N tot kg ha^{-1}*)						May 2011 (*N tot kg ha^{-1}*)						Difference (*N tot kg ha^{-1}*)					
	A0	**A1**	**A2**	**P0**	**P1**	**P2**	**A0**	**A1**	**A2**	**P0**	**P1**	**P2**	**A0**	**A1**	**A2**	**P0**	**P1**	**P2**
0-30 cm	39.1	41.3	40.7	50.2	51.1	53.7	36.9	26.7	25.6	19.9	22.4	30.0	2.2	-14.6	-15.2	-30.3	-28.6	-23.7
30-50 cm	54.7	59.3	56.9	63.6	65.9	59.6	56.1	34.7	39.3	12.5	41.5	33.2	-1.4	-24.6	-17.6	-51.1	-24.5	-26.4
50-80 cm	60.5	68.1	65.1	64.8	63.4	69.1	53.1	49.5	59.8	9.6	41.8	47.4	7.4	-18.6	-5.3	-55.2	-21.6	-21.7
80-90 cm	49.9	50.7	47.2	63.2	64.8	59.9	46.7	49.5	59.8	10.2	39.1	41.9	3.2	-1.2	12.5	-53.0	-25.8	-18.0
TOT	204.2	219.4	210.0	241.8	245.3	242.3	192.8	160.4	184.4	52.2	144.8	152.6	11.4	-59.0	-25.5	-189.6	-100.5	-89.8

3.7 N balance

After the end of the experimental campaign, it was possible to elaborate a N balance, to represent the N dynamics in the FIA and in the permanent meadow. The N balance should be put in comparison with the difference in soil N measured after the first year of experiments. As shown in table 8, the establishment of a crop, otherwise the initial stage, it's a phase in which we have losses of soil fertility. This phenomenon is worsen when there is an high initial N content in soil, as in our case study. In FIA thesis the most important input was the N coming from fertilization, while the most important output was the N lost via leaching. In the permanent meadow the most important output was the N retained by herbaceous biomass. Another output was the denitrification that, including an error, has been assumed to be the missing part to close the N balance. It is noticeable the higher value of denitrification for A2 thesis, probably due to the higher fertilization level. During the initial stage of SRF in the FIA, high levels of leaching have been recorded. The high denitrification could be linked to excessive amounts of distributed digestate, which can lead to anaerobic conditions in soils. The removal of herbaceous biomass in the permanent meadow contributed to negative values, as a consequence of the high N uptake by weeds. Despite this, leaching in the traditional systems has been consistent and related to the unfavorable soil structure. Some clues suggested that denitrification was an ongoing process: (i) the measured denitrification rates via acetylene block technique showed positive results in all the measuring campaigns, with an average rate of 1±0.1 g N-NO_3 ha^{-1} day^{-1}; (ii) the N-NO_2

concentration in tension lysimeters was 0.42 mg/l, suggesting an active denitrification, with four isolated peaks over 1 mg/l, indicating that the limiting condition is the availability of the labile organic substrate, that usually lead to transient N-NO_2 accumulation (Mastrocicco *et al.*, 2011; Nair *et al.*, 2007); (iii) the average redox potential measured in the tension lysimeters was -112±7 mV, indicating anoxic-hypoxic conditions suitable for the denitrification in soils (Zhou *et al.*, 2012). All the above mentioned clues can be considered as a proof of the ongoing denitrification process, although they cannot be used directly to quantify this process, which was then estimated via the mass balance of table 9.

Table 9: Comparison of the N (*kg ha^{-1} year^{-1}*) balance among the thesis.

	A0	**A1**	**A2**	**P0**	**P1**	**P2**
N_f	0.00	163.20	313.00	0.00	156.50	311.40
N_r	28.20	28.20	28.20	33.70	33.70	33.70
Total input	**28.20**	**191.40**	**341.20**	**33.70**	**190.20**	**345.10**
N_L	35.21	81.38	111.24	14.82	34.95	82.88
N_{gb}	6.00	24.00	36.00	188.00	256.00	340.00
N_{wb}	19.90	18.60	25.70	0.00	0.00	0.00
N_e	0.00	3.46	4.60	0.00	5.35	8.11
Total output	**61.11**	**127.44**	**177.54**	**202.82**	**296.30**	**430.99**
N_{den} + N_{err}+N_a	**-32.91**	**63.96**	**163.66**	**-169.12**	**-106.10**	**-85.89**

4. Conclusions

The hypothesis to be investigated in the present work was to verify the possible increased capacity of the FIA in limiting N losses during the initial stage of growth, compared to a more conventional cropping system (permanent meadow). This could depend on the particular hydrological management of these areas and on the presence of plants with root systems capable of achieving a significant development in terms of depth from the soil surface and support the processes of assimilation and denitrification. The emissions of N were slightly lower in the forested infiltration systems than in the meadow. Furthermore, these difference should be higher due the chambers method, that cannot consider the N uptake by gaseous exchange with leaves. There was a proportionality between the amount of emissions and the amount of slurry distributed. The total emission values in FIA and in the permanent grassland were relatively low compared to what could be initially assumed. As stated by Balasus *et al.* (2012), the literature on N fertilization in short rotation coppice systems during the early stage is inconsistent, hence these results are a contribute to enrich this field of research. In comparison with reference literature of traditional agricultural system, these percentages could be considered quite low. N balance has shown higher efficiency in the FIA compared to the permanent grassland, most probably due to storage of N in woody biomass. In particular, at high fertilization rates a considerable leaching reduction in the FIA with respect to the permanent grassland was observed, which is a primary aspect in highly vulnerable zones characterized by elevated soil permeability like the one considered in this study. A sustainable management of slurries is required and could enhance yields of energy crops, which can improve environmental parameters thanks to phytoremediation.

Acknowledgments

We thank Mezzalira G., Correale F., Della Venezia F. Zanin R., Ruol G. and Albanese D. for their contributions on planning and field activity. We thank the Consorzio Brenta for irrigation system management and the private Farm “Agrifloor Di Cerantola Paolo

E C. S.S." that hosted the experimental activity. This work was supported by Veneto Region Authority and Veneto Agricoltura within "RIDUCAREFLUI" and "REDAFI" projects.

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3.2 Nitrogen emissions from mature short rotation coppice plantations

Publication prepared for technical report of Veneto Agricoltura

Publication: Nitrogen emissions in mature short rotation coppice plantations

1. Introduction

The emission of gases (NH_3, CH_4, N_2O, CO_2) as a consequence of the spreading of slurry is an issue of environmental relevance, recognized by international protocols (Gothenburg 1999; Kyoto 1997) and the growing focus of scientific research. In the case of the distribution of slurry that comes from digestion plants (digestate), the most considerable gas emitted is ammonia (Erisman *et al.*, 2003). Po Valley is an important area for European Agriculture that has been bound to a number of regulation limits due to high level of nitrogen pollution, especially nitrates in the water bodies. According to the nitrate directive, the majority of Po Valley can be considered as a nitrogen vulnerable zone (NVZ), with a maximum organic fertilization of 170 kg N ha^{-1} $year^{-1}$.The great concern for the limits of nitrate directive has led to a number of studies on fertilization, in order to study the diverse effects on agricultural land and water bodies. Ammonia emissions following land application of slurries contribute to a significant part of the total ammonia emissions from agricultural sources. This problem is particularly pronounced in European region where there is an high density of livestock, and the scarce availability of agricultural land for slurry spreading. It's not a casualty that most of the studies in this field come from Denmark and Netherlands (Yague and Bosch Serra, 2013). On European scale, there is a considerable interest in improving techniques for spreading and finding mitigation solutions, considering both emissions and leaching problems. A number of field studies have been done in these years, in order to give a contribute on which are the best techniques to limit nitrogen pollution, among these our projects financed by Veneto Agricoltura in two Italian sites. The projects aimed to prove the plants specialized in the production of woody biomass on reducing the nitrogen content in the slurry and digestate. For these projects interdisciplinary and experimental studies have been performed using digestate from biogas plants in order to study the effect of organic fertilization on biomass yield, soil and environmental variables in fields, making a comparison between permanent succession crop with maize and Italian ryegrass and a plane plantation in Tezze sul Brenta (VI), and poplar thesis in Monastier (VE). The group of researchers involved were hydrologist from Ferrara University, biologist from Bologna University, and agronomists from the University of Udine. The different processes that are sinks or sources for nitrogen pollution in the agro-ecosystem were taken together in a nitrogen balance assessment, which is the main scientific result for this kind of studies (Balasus, 2012). Our unit of research from University of Udine has worked on gaseous emission, developing a methodology at the beginning of 2013.

2. The development of the Methodology

The NH_3 dynamics in the continuum soil-plant-environment is difficult to detect, because of the high reactivity of ammonia, its tendency to bind with plastic surfaces and water, that cause adsorption on analyzers and sampling tubes (Ferrara, 2010). There is no standard method to investigate ammonia volatilization, but the techniques of sampling is dependent on the specific case study. A literature analysis has been done in order to identify the best methodology for our experiments: the sampling of ammonia and nitrous oxide emissions from the application of digestate in comparative studies. Chambers method has been identified as the best option, because of the small size of plots and the neighborhood of comparative thesis. In fact the well-known micrometeorological method suffer from interferences if the thesis are located close (McGinn and Janzen, 1998). Furthermore, the availability of a PAS technology allows to measure with great precision the concentration of target gases. This technology adopts the photo-acoustic effect, based on photons flux that hits particles and molecules and the conversion into acoustic waves, recorded by high sensitivity microphones. This process was discovered and studied by Alexander Graham Bell in the late

1800s, but it collected little interest until the 70s, when there was a greater attention to the phenomenon because of the development of laser techniques and sensitive measurements (Innova Report). From that moment, the instruments that adopt the photo-acoustic principle were used in order to monitor a wide range of gases for various applications, such experiments in the laboratory, environmental measures, and anything that may have to do with the measurement of gases. There is an important difference between concentration and emission measurements. The photo-acoustic monitor can give a reliable assessment of the concentration of a gas, but the main interest is in getting an assessment of the emission rate: to obtain this value, the photoacoustic monitor has to be linked to chambers, that can vary largely as seen in literature. The current types of chambers used for agricultural studies vary in basal sampling area from <1 m^2 to 5.76 m^2 to 64 m^2 (FAO, 2001).

Table 1: A comparison of chambers found in literature

Author	gas detected	material	diameter (m)	height (m)	volume (mc)	flux (l*min)	collar (m)
Predotova	NH_3, CO_2, N_20	PVC, Teflon	0.3	0.11	0.01	closed chamber	0.06
Lompo	NH_3, CO_2,N_2O	PVC, Teflon	0.3	0.11	0.01	closed chamber	0.06
Acevedo	NH_3, CO_2	stainless steel	0.32		0.0123	closed chamber	0.05
Lovanh	NH_3,CO_2, CH_4 ,N_2O	aluminum	?	0.1	?	closed chamber	no
Mis-	NH_3	stainless	?	?	40		

selbrook		steel					
Wheeler	NH_3	stainless steel	0.38	0.15	0.057	3,25	no
Capareda	NH_3, H_2S	acrylic	0.495		0.065		no
Fleesa	N_2O, CH_4	PVC	0.3	0.15			0.07
Levy1	N_20, CH_4	PVC	0.63	0.29			0.05
Levy2	N_2O, CH_4	PVC	0.38	0.23			0.05
Conen	N_2O	Plastic rings	0.4	0.2			0.07
Skiba	N_2O, CH_4	PP	0.4		0.017		0.05
Nakano	CH_4, CO_2	TEF		0.2		1.01	0.02
Yamulki	N_20, CH_4, CO_2	aluminum	0.4	0.2			
Gholson	VOC	acrylic			0.03		variable

The chambers are placed on the top of the soil, and the gases accumulate inside the chambers. In our field experience, we have noticed that to avoid problems of over-saturation, the chambers should be put on the soil for no more than 12 minutes of sampling. The photo-acoustic monitor, in the mentioned above period, detects 7 sampling points (every two minutes). Obtaining the sampling points, a regression line can describe the emission rate.

Fig. 1: Ammonia sampling points

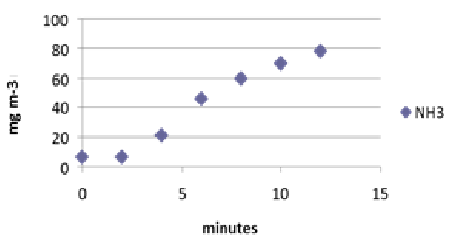
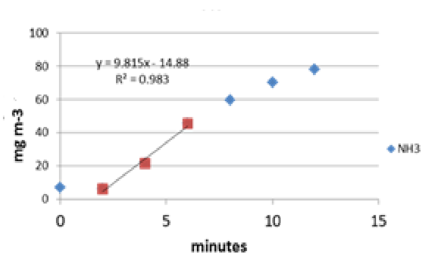


Fig. 2: Ammonia regression line



Once decided to choose this methodology, because of the characteristics of our case studies, some laboratory experiments on chambers have been conducted, in order to decide materials, modality and size of the chambers. At the beginning of 2013 tests were carried out for the detection of emissions of ammonia (NH_3). An aqueous solution obtained with 1 ml of a solution of NH_4OH (30 % NH_3), diluted in 300 ml of H_2O, was used for tests. The material tested were stainless steel tube, an aluminum tube and a plastic bucket. The results of the preliminary experiments, doing repetitions and comparisons among different ammonia concentration, proved that stainless steel is the best option to detect ammonia. Regarding the modality of chambers, the Environmental Protection Agency (EPA) recommends the technology of dynamic chamber for detecting the emission of pollutants. However this is not an absolute indication, and for technical operative reasons, in our case the simple closed chamber with reflux of air has been adopted. Teflon tubes were used to link the photo-acoustic monitor, because teflon is the best inert material that prevents one of the main problems of the detection of ammonia: its reactivity with the surfaces. In literature, there is no clear uniformity in the shape and size of the closed chambers. However the residence time in the chamber, given for a specific reflux, has been useful in dimensioning the stainless steel chambers. The residence time, τ, is defined as the volume of the chamber divided by the flow of ventilation. Typically it is required three or four τ to reach steady state. In our case , by applying a flow of 3 liters to the room we have chosen that volume 8.95 l, and the steady state is reached after 6 minutes. or after 3.3 τ . This is coherent with the recommendations of Eklund (1992), who suggested between 3 and 4 τ for the achievement of steady state. The stainless steel chambers has shown a good capacity to detect high amounts of NH_3, without incurring saturation.

3. Experimental set up

Experiments on the effect of organic fertilization on the mature stage of short rotation coppice crops have been conducted in two sites in Veneto Region. The first site was located in Monastier (TV), where a poplar plantation has been established in the late spring of 2013. The soil is characterized by an high content of clay and defined as silty clay soil. The experiment was conducted considering four thesis, divided by pig slurry and digestate, and with different level of fertilization: 170 and 340 kg ha^{-1} year^{-1}. The technique used for slurry application was the injection of slurry.

Fig. 3: Monastier Poplar clone “Baldo” and spreading technique with injection

The second site was located in Tezze sul Brenta (VI), included in the drainage basin of the lagoon of Venice. The scientific work has been based on the comparison between a crop succession Maize- Italian ryegrass and a Short Rotation Coppice of Platanus Hyspanica, established in May 2009 in a forested infiltration area (FIA). The experimental site was set up with parallel ditches (1 m depth) mainly to recharge the aquifer from diverted water of the closest stream (Brenta River) during high-water periods and out of irrigation season. In Tezze sul Brenta the main focus was on the efficiency of FIA in prevent nitrogen pollution, using slurry produced in biogas plant and distributed with a trailing hose technique. In the succession Maize- Italian ryegrass the distribution was done with a trailing hose technique with the immediate incorporation of slurry. In the first year were done three slurry distribution, in 2014 a single spreading event. Two thesis have been done for short rotation coppice crops, A1 (170 kg N ha^{-1} year^{-1}) and A2 (250 kg N ha^{-1} year^{-1}), using slurry. For the succession maize Italian ryegrass has been done a thesis M1 with 170 kg N ha^{-1} year^{-1}, using chemical fertilizer.

Fig. 4: Chambers methodology for the comparison between Maize and Platanus Hyspanica and trailing hose technique applied in Tezze sul Brenta

4 Results and discussion

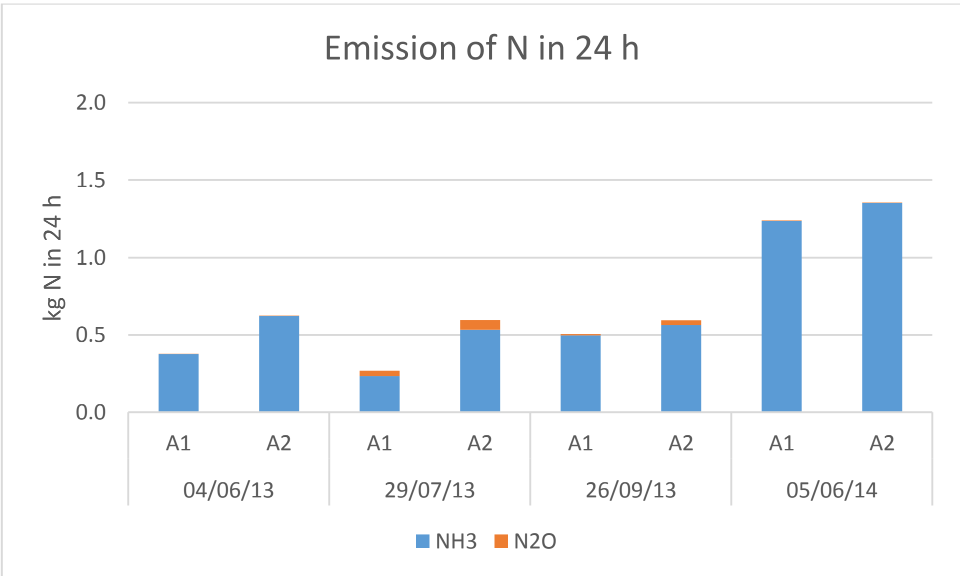
During two years (2013 and 2014) experimental measures have been taken for ammonia and nitrous oxide. The nitrogen emission, in Tezze sul brenta and Monastier, were coherent with literature references for the specific spreading techniques (injection/trailing hose). For Monastier, data on NH_3 and N_2O emission were negligible. The absence of significant emission rate has been attributed to the immediate and deep infiltration of liquid slurry. The opportunity of this management choice will be discussed in following works, because there is incertitude on the effect that this technique could have on nitrogen losses via leaching. Conversely, emission data of the experimental site in Tezze sul Brenta are considered interesting and variable in function of experimental conditions, as presented hereinafter. The lower ammonia emission (NH_3) of the traditional system (1-2% of total N) compared to the forested infiltration area (4-7% of total N) are caused by the faster infiltration of slurry that is related with the incorporation of slurry.

Table 2: Results from Tezze sul Brenta site, comparison of short rotation coppice thesis (A) and maize Italian ryegrass thesis (M)

	Thesis	N- NH_3	N-N_2O	Total N	N em./N dis.
		kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	% (mean value)
First Year	A1	9.41	0.39	9.79	5.95
	A2	14.61	0.80	15.41	6.40
	M1	8.72	1.01	9.73	4.97
Second Year	A1	10.51	0.02	10.53	6.54
	A2	11.49	0.03	11.52	4.86
	M1	2.32	0.61	2.93	0.96
Mean 2 years	A1	9.96	0.21	10.16	6.25
	A2	13.05	0.42	13.47	5.63
	M1	5.52	0.81	6.33	2.97

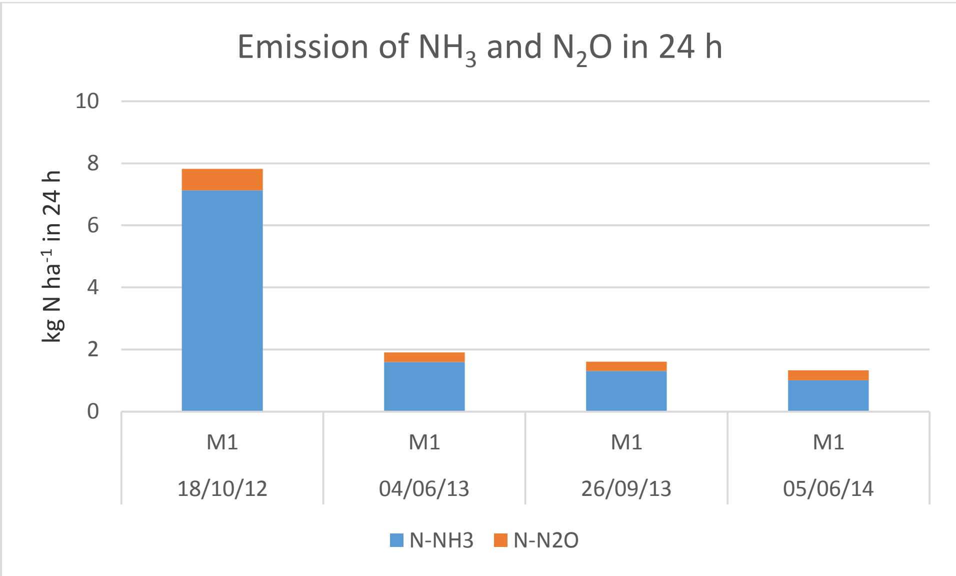
Considering the whole experimental period, the cumulative emissions have been higher for the short rotation coppice thesis, as a consequence of the different techniques applied in the two systems. The A2 thesis have always evidenced higher emissions respect to A1 thesis. During year 2013, the cumulative emission has been resulted 9.8 kg ha^{-1}, correspondent to 6 % of the distributed nitrogen for A1 thesis, and 15.4 kg ha^{-1}, correspondent to 6.4% of the distributed nitrogen respectively for A2 thesis. These values are low compared with other experiments performed with trailing hose technique (Webb *et al.*, 2010). Lower ammonia volatilization could be caused by the shadowing of slurry thanks to trees, and secondly the reduce of wind speed for the plantation, that lead to lower values of emission respect to traditional crops. In 2014 for a single spreading event, the emissions were higher, but for A2 thesis there was lost a lower percentage of applied nitrogen respect to A1 thesis (7.1 % versus 8.8%). Regarding Forested Infiltration Area (FIA), in A2 thesis the emission of nitrogen in the single spreading event of 2014 were higher respect to the other three spreading events in 2013. In 2014, the emission of nitrogen from A1 thesis are almost equivalent to A2 thesis, as a result of the prolonged cover of soil by slurry. The partition of the annual amount in three or four organic fertilization did not guarantee lower cumulative emissions than a single intervention, contrary to the outputs that come to other studies (Bourdin *et al.*, 2014; Van Es *et al.*, 2006). However, despite the emission of ammonia could be higher with the partition of the annual amount of slurry, considering the whole nitrogen fate, including leaks in water and denitrification of nitrous oxide, it is a management system more convenient respect to the single spreading event, according to other research studies.

Fig. 5: Nitrogen emission from short rotation coppice crops



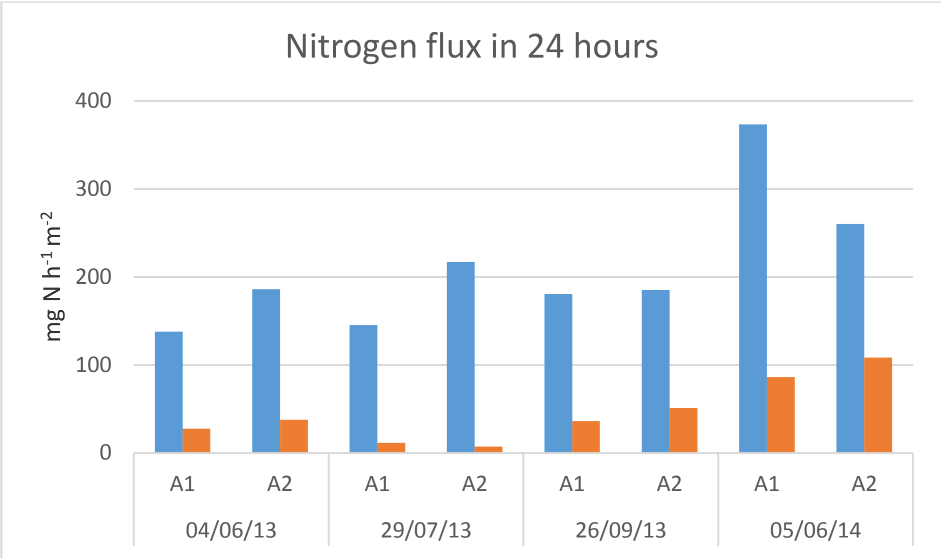
Regarding the M1 thesis, the emission from the maize - italian ryegrass thesis was particularly high in October (7.8 kg N ha^{-1}), caused by the broadspread of slurry. The techniques of spreading have a great importance in influencing the amount of ammonia emission, as can be seen in figure 6. The emission measured in the following spreading events were lower (1.3 and 1.9 kg N ha^{-1}), because of the incorporation of slurry within the first hour after spreading.

Fig. 6: Nitrogen emission from maize ryegrass thesis



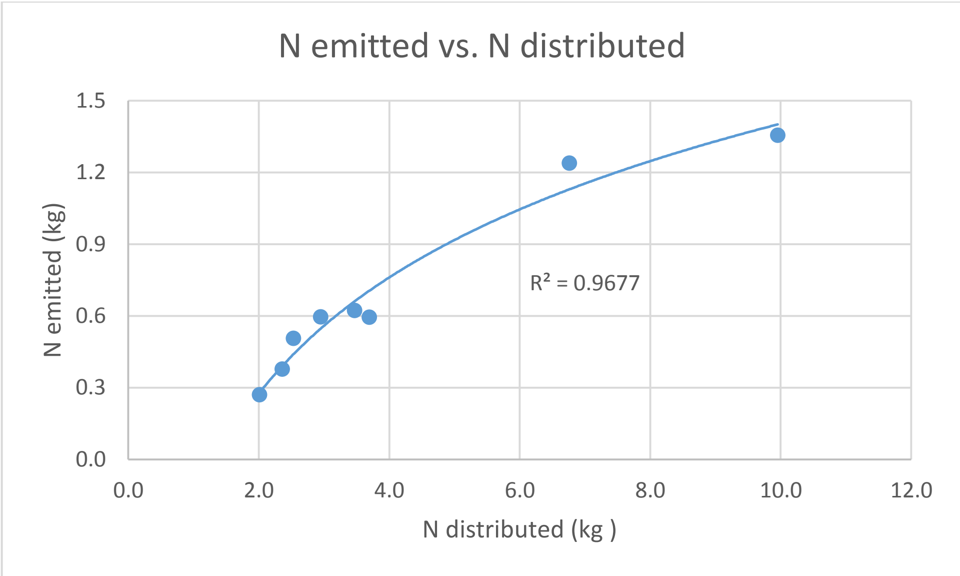
Considering the A thesis, the ammonia emission has showed the characteristic trend, with high emission immediately after spreading and a great reduction within the 24 hours. This phenomenon was particularly pronounced with higher temperature, which occur in the July experimental campaign, with a great emission of ammonia during the first hours.

Fig. 7: The reduction of nitrogen flux within a day after spreading (in blue the emission at time after spreading, in orange the emission after 24 hours)



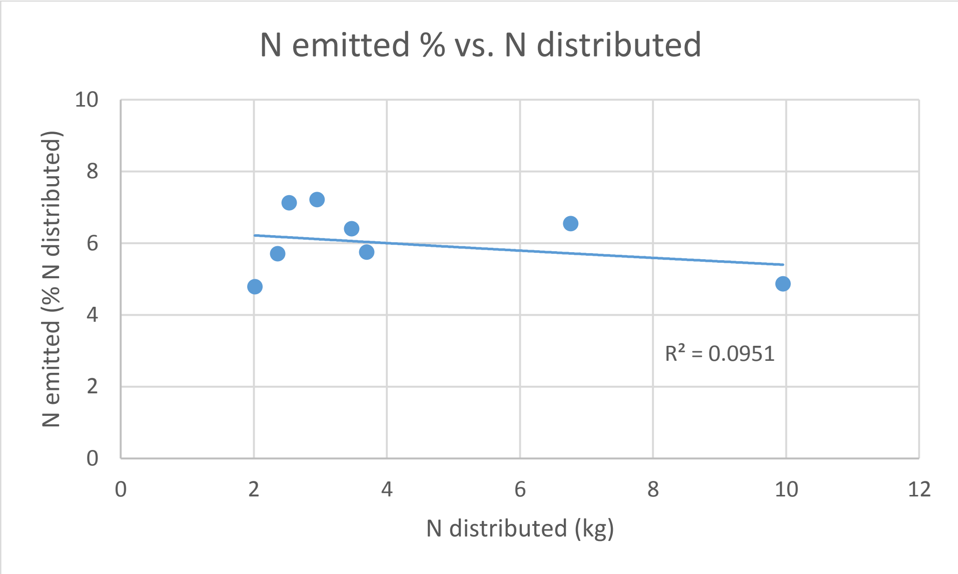
The ratio nitrogen emitted over nitrogen applied has been only slightly decreasing in function of distributed dose, varying from 4.8% to 7.2 %. The relationship between nitrogen distributed and nitrogen emitted don't show the characteristic sigmoid pattern of other environmental variables. The emission rate has resulted to be lower after 24 hours for all the thesis, especially in the spreading event in July 2013, characterized by high temperature and, consequently, high evaporation rates. In 2014 for the experimental campaign there are quite high value of ammonia emission after 24 hours, caused by huge amount of slurry that was not infiltrated in soil.

Fig. 8: Correlation between distributed and emitted nitrogen in kg



In percentage it has been lost around 6% of distributed nitrogen. Indeed the crucial parameter is not the amount of slurry distributed, but the coverage of soil by slurry, that gives higher values for A2 thesis during the first 24 hours after spreading. The spreading technique has a great influence on this parameter, with a remarkable difference between technique that concentrate slurry and the traditional broad spreading that covers the whole soil. The nitrogen emitted rises with the increase of the dose, but the percentage of nitrogen emitted is not significant, as in figure 9.

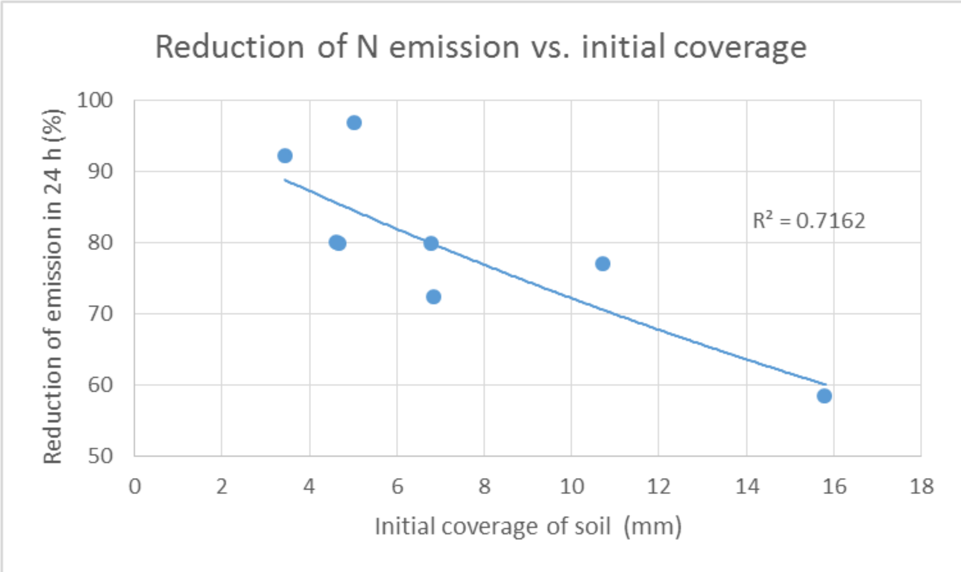
Fig. 9: Correlation between distributed and emitted nitrogen in percentage



The key point is that soil influences infiltration of slurry, as seen in figure 10. The emission during the first 24 hours is conditioned by the surface covered by slurry, more than the amount of nitrogen distributed. The flux of ammonia has been resulted inversely proportional to the soil coverage by slurry. The key point is that soil influences infiltration of slurry. The emission during the first 24 hours is conditioned by the surface covered by slurry, more than the amount of nitrogen distributed. With coverage of 3.5 – 5.0 mm the emission rate of NH_3 after 24 hours has shown a reduction of 96.8% respect to emission rate at time zero, whereas with coverage of 16 mm the emission rate has been reduced only of 58.4%.

Fig. 10: Reduction of nitrogen emission

in function of the initial coverage of soil by slurry



Conclusion

The scientific output that comes from this publication can find a place in the context of other works on this topic. Regarding the spreading of slurry, in our case study digestate, a number of techniques can be found in literature. The technique of spreading is considered the crucial factor in determining ammonia emission, and it has been confirmed by our experiments in maize thesis. Considering the comparison between agricultural systems, the mitigation effects of short rotation coppice rise from the shadowing of soil, the interception of ammonia by leaves, the capability of root zones to retain reactive nitrogen. However the most crucial factor is the technique to apply slurry on agricultural land. Little is known about the effect of organic fertilization on short rotation coppices and the environmental and economic trade off of these systems respect to tradition crops are still a matter of debate. Nutrient removal in SRC crops seems to be far greater than in conventional forestry due to the high density of the shoot population and the frequency of coppicing. However, in Florobasco the application technique with injection of slurry can be considered the best abatement strategy for emissions. The unit of research has investigated if this kind of abatement (zero emission) is desirable, because if all the ammonia nitrogen is injected in the soil, losses of reactive nitrogen as leachate can be very high. Regarding current agricultural research, so the academic point of view, the organic fertilization in short rotation forestry can be an interesting niche in studies on manure management and bioenergy. Further development of this study will include the analysis of GHG emission, compared between the two systems, that will find place in a new publication.

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4. Short Rotation Coppice: the ESRC model

The third work presented in this thesis aims at modelling the environmental and productive aspects of SRC crops, with modules on the nitrogen dynamics in these agrosystems. The core of this work is on the productive responses of short rotation coppice crops (willow and poplar) under different fertilizations, but it has been developed also a nitrogen efficiency module that will be used for further works on the environmental consequences of Short Rotation Coppice. The influencing factors in ammonia volatilization have been widely discussed in the 2000s, and summarized exhaustively in Huijsmans thesis (2001) and Sommer review (2003). The effect of these factors has been considered in many studies during the last decades, each of which included two or three factors (Horlacher and Marschner,1990; Sommer *et al.*, 1991; Sommer *et al.*, 1991; Braschkat *et al.*, 1997; Menzi *et al.*, 1998). Performing sensitivity analysis, it has been possible to study the relationships of many parameters involved in the process of volatilization, and assess their relative importance (Søgaard *et al.*, 2002). In these years great attention has been posed on strategies to mitigate climate change and establish a carbon free market for European Union. Among these strategies, bioenergy is recommended because of the economic return of biomass and the advantages for the environment that are associated with the agricultural management of some bioenergy crops. Recently in this area of research Short Rotation Coppice crops have been collecting great interest, because of the potential yields of poplar and willows and the opportunity to use slurry as a valuable fertilizers. The term Short Rotation Coppice (SRC) refers to cultivation systems using fast-growing tree species with the ability to resprout from the stump after harvest. Harvest occurs in short intervals, 2-6 years, and management practices (soil preparation, weed control, planting, fertilization, harvest, etc.) are more similar to those of agricultural annual crops than to forestry (Heller *et al.*, 2004). The consumption of wood for energy in the EU has been increasing in recent times. The demand for wood in the EU is very likely to increase in the period to 2020 and potentially beyond, with most of this due to a significantly greater increase in the demand for wood for energy. SRC for production of biomass for heat and electricity is considered a very promising means to meet the different targets set in Europe to increase the amount of renewable energy (EEA, 2006). Political drivers have stimulated the interest in growing and processing biomass crops as a source of renewable energy; different incentives for growing SRC have been introduced in several European countries. Currently, there are c. 14,000 ha willow SRC cultivations in Sweden, mostly on productive agricultural land, and smaller areas of SRC in Italy (c. 6,000 ha, mostly poplar), Poland (c. 3,000, mostly willow), the UK (c. 3,000 ha, mostly willow), Germany (c. 1,500 ha, mostly poplar), and other European countries. Management of intensive short rotational system in some cases have shown high productivity and it is also a promising crop option on marginal agricultural lands and waste disposal sites (Isebrands and Karnosky, 2001; Laureysens *et al.*, 2004). Multiple environmental benefits have been found in these systems (Berndes *et al.*, 2004). SRC is generally considered to improve the water quality relative to conventional agricultural crops in a given area due to the management practices of SRC (weed control only during the establishment phase, tillage only before the establishment phase, and lower inorganic fertilization than other crops). Most of the studies for SRC concerning water quality have dealt with N and P leaching to groundwater since these elements are considered responsible for eutrophication in water bodies. The impact of SRC on soil affects C sequestration, nutrient cycling from litter and soil microorganisms. The phytoremediation ability of SRC species also depends on soil impact. Nair *et al.* (2009) have reported that C sequestration in arable soils depends on a number of site-specific biological, climatic, soil and management factors. Reported values for total C sequestration under SRC are significantly higher than under arable soils with annual crops. Poplars and willows are used for phytoremediation to clean soil from hazardous compounds such as heavy metals or organics, based on the function of the plants against hazardous compounds via different processes (Glass, 1999). The phytoremediation potential of willows and poplars has been reported to be high based on the combination of high accumulation of metals in the plant tissues together with the high biomass produced. The impact of SRC on biodiversity is positive, especially when it is used as a web on landscape, enhancing the edge effect that is well known to increase biodiversity (Christian *et al.*,1997). Among the positive aspects, a crucial thing that are studied in research projects is the opportunity to use wastewater, slurries, digestate to fertilize crops, and to achieve both the environmental, energy and farmers goals (Dimitriou and Aronsson, 2005). This is considered a strategy for facing nitrogen challenge using phytoremediation, a cost effective plant-based approach. Despite the importance of these studies, still little is known about the nutrient use and efficiency of poplar SRCs, and how the amounts of trapped nitrogen can vary according to factors such as site conditions (Paris, 2014). In literature there are many works on SRC crops, but still lacks a homogeneous analysis on the potential for European lands and how much climate and soils can affect the productive targets of these crops. Many of the studies are experiments on field that are restricted to a specific agricultural management and that cannot be generalized for the wide range of conditions found in European Agriculture. The diverse environmental and economic conditions that have to be analyzed, should suggest the adoption of modelling approaches in order to improve both yields and environmental quality of SRC crops. Some of these studies have been cited in the following work on the ESRC model, that is a work based on the development of a model and its calibration, using data from diverse locations in the North of Italy. This part of my PhD researches was important for the understanding of the complex influences that occurs bidirectional between SRC and the environment. Indeed, these environmental and productive models should been validated on the basis of field experiments, collecting a vast number of data from different plantations. The third work presented in this thesis aims at modelling the environmental and productive aspects of SRC crops, and it includes a module that simulates the nitrogen dynamics in these agrosystems. The core of this work is on the productive responses of SRC crops (willow and poplar) under different fertilizations, but it is a useful tool that will be used for further works on the environmental consequences of Short Rotation Coppice. A modelling approach allows to find the best solution for the land use, in order to achieve maximum positive effects and minimize potential negative effects from large-scale SRC cultivation on agricultural soils to produce biomass for energy. Proper site selection and management adjustments should be implemented taking into account the research results related to each of the aspects affected by SRC cultivation. Further development of this work will be the use of data that come from my "on field" works to validate the module for the simulations of nitrogen emissions. Indeed the module on nitrogen dynamics can be implemented with calibrations on a wide range of emission data. The simulations of environmental variables that are in the ERSC model, can give an important contribute for the understanding of the positive effect that these crops have on the agricultural systems. Despite all the expected positive environmental impacts of SRC, farmers need to be convinced to grow the crop. These difficulties may be overcome with simulations using reliable models, that give a statistical mean of yields under different climatic scenarios.

Prepared for Biomass and Bioenergy Journal

ESRC model for short rotation woody coppice

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Abstract

Rising atmospheric CO_2 concentrations and their association with global climate change have led to several major international initiatives to reduce net CO_2 emissions, including the promotion of bioenergy crops such as short rotation coppice willow and poplar. These crops are an interesting opportunity for European agriculture that aims at reducing the dependence of fossil fuels resources and reaching European environmental targets. Here it is presented ESRC, a new model to simulate poplar and willow growth, developed in SEMoLa environment. The effects of soil type, irrigation, nitrogen fertilization and rotation cycle on growth and yield of willow and poplar clones were studied, using independent dataset from two Italian sites, Osoppo and Lombriasco. A literature survey on crops parameters have been done as a preliminary study to operate with the model, and it is a valuable s results of this work. After a sensitivity analysis crucial parameters were identified, calibrations on yields were performed, obtaining significant statistical results. ESRC has been proved to be a comfortable and reliable tool for stakeholders, because of the high usability that arises from the user-oriented implementation approach used for its development. The SEMoLa source code of the model is almost self-explained and can be easily modified and updated also by not-programmer users. However , the model requires a good characterization of regional genetic characteristics of willow and poplar clones in order to obtain credible values.

Keywords

modeling, short rotation coppice, genotype×soil×climate×management trial combination, model calibration, bioenergy, poplar, willow

Model availability

Name of model: *ESRC* – Evaluation System for Short Rotation Coppice (version 1.0)

Main Developers: Francesco Danuso, Fabrizio Ginaldi (University of Udine)

First available year: 2015

Software requirements: Windows® XP or newer versions, SEMoLa platform (SEMola v6.8.1 installation package, freely downloadable on http://www.dpvta.uniud.it/danuso/docs/Semola/homep.htm) to run model, PowerBasic console compiler (Pbcc.exe, version 5 or higher, PowerBasic Inc., commercial) for model development, HTML help compiler (HtmlHelp.exe, copyrighted and freely available by Microsoft) for model help creation.

Program language: SEMoLa (Danuso and Rocca, 2014)

Availability: freely downloadable on http://www.dpvta.uniud.it

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1. Introduction

Due to increasing energy use, price instability of fossil fuels, insecurity of fuels supply and Greenhouse Gas (GHG) emissions, number of activities are undertaken in order to reduce them. The Renewable Energy Directive sets a target for the European Union (EU) to consume 20% of its final energy from renewable sources by 2020 (EC, 2009) and further targets are under discussion. This will lead to a substantial increase in the demand for bioenergy, that is expected to play an important role in view of possibility to store and convert it to energy on-demand (Rentizelas et al., 2009).

However, bioenergy production should be consistent with the principles of the EU Resource efficiency roadmap and more efficiently obtained, minimizing negative environmental impacts. The increasing criticism of the sustainability of many first-generation biofuels has raised attention to the potential of so-called second-generation biofuels. Feedstock for second-generation biofuels is usually forest biomass. One of the alternatives to conventional forestry biomass is that deriving from the use of short rotation woody crops, in Europe principally through willow (*Salix spp*) and poplar (*Populus spp*) cultivation. They are promising biomass crops due to their ease of propagation and fast growth ability (Sennerby-Forsee et al., 1992). The EU defines Short Rotation Coppice (SRC) as areas planted with tree species of Combined Nomenclature code 06029041 consisting of woody, perennial crops, rootstock or stools remaining in the ground after harvesting, with new shoots emerging in the following season and with a maximum harvest cycle determined by individual Member States jurisdictions. They are high-density plantations of fast growing trees for rotations shorter than 15 years (McAlpine et al., 1966; Herrick and Brown, 1967; Afas et al., 2008). SRC are distinguished from Short Rotation Forestry that is harvested in longer intervals. The very SRC cultivation scheme has even a plant density higher than 5500 plants ha^{-1} and harvesting cycle of 1-4 years (Manzone et al., 2014).

Management of intensive short rotational system shows high productivity and it is also a promising crop option on marginal agricultural lands and waste disposal sites (Isebrands and Karnosky, 2001; Laureysens et al., 2004). Hence, a rapid expansion of SRC is expected in agricultural areas near heat and electricity plants for biomass combustion. Nonetheless, low woodchip prices and lack of subsidies have been causing SRC production to be still marginal in Europe – in Sweden about 14000 ha (Dimitriou et al., 2011b), in Italy about 10000 ha (mostly poplar), in Poland about 3000 ha (mainly willow) (Dimitriou et al., 2011a), in the UK about 7500 ha (mainly willow) (Lovett et al., 2009), in Germany about 5000 ha, (poplar and willow), and in France 3000 ha (mostly poplar) (Bemmann, 2010). SRC plantation advantages also include lower herbicide and pesticide doses than other agricultural crop and significant environmental benefits in terms of soil organic carbon sequestration (Hansen, 1993; Coleman et al., 2004) and soil erosion protection (Isebrands and Karnosky., 2001; Updegraff et al., 2004). Large-scale deployment of willow and poplar plantations may have potential negative impact on water quantity and quality and on soil through water abstraction, nutrient and pesticides losses to surface and groundwater and soil compaction (Elbersen et al., 2005; Rowe et al., 2009; Dimitriou et al., 2011a). The SRC effect on biodiversity is also questionable, and in some measure dependent on stems age (Rowe et al., 2009).

Given the high variability of yield in commercial stands, knowledge about growth and productivity of SRC crops under different climate and soil conditions is an important criterion in clones selection and management optimization. Obtaining new data through traditional agronomic research is not sufficient, nowadays, to provide needed information for agricultural decisions (Jones et al., 2003). Besides, a crucial problem of these biomass sources is also the misleading or scarce accuracy of data about yields. The understanding of internal and external relation of SRC system and the possibility to forecast yield or to optimize the combination genotype × environment are fundamental and can be made by simulation models.

A model is a simplified representation of a real system based on simplifying assumptions (Abrahamsen and Hansen, 2000). Surendran Nair et al. review (2012) has stated that fourteen models have been used for simulating bioenergy crops including herbaceous, woody bioenergy crops and crassulacean acid metabolism (CAM) crops. The resulting best one indicated for SRC crop simulators are: SECRETS (Sampson and

Ceulemans, 1999), EPIC (Williams, 1989) and 3PG (Landsberg and Waring, 1997). A review of their main features is reported in (Table 1).

Therefore, for an evaluation of agro-energy chain in second generation biofuel production systems, sustainability assessment is required also in management, energy and environmental terms.

For these reasons it has been developed *ESRC* (Evaluation System for Short Rotation Coppice) which is a multi-year, multi-crop, daily time step SRC system model developed to provide stakeholders with information about plantation productivity over time and space. *ESRC* has a modular structure and each module represents a different part of the SRC system. The model takes into account the variability of soil characteristics, climate, SRC clones features and agricultural techniques. The first two factors are site-specific and are a part of variability that is to be considered, independently from farmer choices. The latter two variability sources are optimizable as directly controllable by farmers.

ESRC has been implemented using SEMoLa (Simple, Easy to use, Modelling Language, Danuso, 1992; Danuso and Rocca, 2014), a declarative language for the development of simulation models and agro-ecological knowledge integration. SEMoLa allows the simulation of dynamic systems by the construction of deterministic and stochastic models, states-based (stocks and flows) or elements-based (as Individual Based Modelling), considering also discrete events. Ontology of SEMoLa language originated from the System Dynamics approach, proposed by Forrester (1961) and widely used in describing continuous systems (Muetzelfeldt and Massheder, 2003).

As a result of model comparison (Table 1), *ESRC* can be placed in a niche in the demand of new models: i) assimilated carbohydrates partitioning dynamic between above and belowground biomass is based on a resilience principle and allows primarily to simulate plant response after disturbance events (sprouting after cutting event); ii) Runtime computation of the stump survival rate, which influences growth processes, meets the need of reproducing stand ageing effect on biomass production over time; iii) biomass partitioning into four pools (fine roots, coarse roots, stems and leaves) leads to a more realistic dynamic representation of soil organic matter turnover and carbon balance; iv) *ESRC* computes a dynamic energy and carbon balance of the plantation.

The high *ESRC* usability arises from the user-oriented implementation approach used for its development. The SEMoLa source code of the model is almost self-explained and can be easily modified and updated by not-programmer users too.

The objectives of this paper are: i) to present *ESRC* and ii) to perform a model calibration for different poplar and willow clones grown under different management conditions and environments, in terms of both soil and climate.

Table 1. Comparison of four bioenergy models for crop growth, soil carbon, nitrogen and water dynamics and stress factor estimation.

Model	ESRC	EPIC	3PG	SECRETS
Phenological development	4 stage	4 stage	PDC	4 stage
Leaf growth	SLA	FA	FA	FA
Radiation interception	EC	EC	EC	Direct/diffuse radiation
Biomass	RUE	RUE	PR	DF
Partitioning biomass	4 pools	2 pools	3 pools	3 pools
Water modelling	Two bucket model	Multiple bucket	Single bucket	Two bucket
Water processes	R, E, Tr	R, E ,Tr, C, F, Sn	R, E, Tr, C	R, E, Tr, C
Nitrogen processes	Mi, D, N, L	Mi, D, N, L, V, Im	No explicit subroutines	Mi, D, N, V, Im
Carbon pools	M, S, P, H	M, S, P	NA	M, L
Carbon loss	G	G, L, Er	NA	G, L
Agricultural practices	Yes	Yes	NA	NA
Type of stress	W, T, Nu	W, T, Nu, A	W, T, Nu	W
Adjusted variable for stress	Biomass	Biomass, LAI	LAI, photosynthesis, root growth	LAI, photosynthesis
Energy balance	Yes	Yes	NA	NA
Carbon Budget	Farm scale	Yes	NA	NA

Abbreviations: PDC, phenological development curve; SLA, specific leaf area; FA, functional approach; EC, extinction coefficient; RUE, radiation use efficiency; PR, photosynthesis and respiration approach; DF, de Pury and Farquhar approach; C, canopy interception; R, infiltration/runoff; E, evaporation; Tr, transpiration; F, freezing; Sn, snow melt; Mi, mineralisation; Im, immobilisation; D, denitrification; N, nitrification;

V, ammonium volatilisation; L, leaching; M, microbial pool; S, slow pool; H, humus pool; P, passive pool; G, gaseous loss; Er, erosion; W, water; T, temperature; Nu, nutrient; A, aeration; LAI, leaf area index; NA, Not available.

2 Modeling approach and *ESRC* components

It is common to deal with complex system consisting of many interrelated sub-systems. This naturally leads to models made by sub-models and a modules-oriented programming approach (Jones et al., 2001; David et al., 2002; Donatelli et al., 2005; 2006a,b). Modularity guarantees code ease maintenance, granularity of the approaches implemented, tools reusability and cross platform capabilities (Meyer, 1997). Isolation of modelling problems belonging to specific domains allows collaboration among specialists in specific sectors which can develop their own sub-models. For these reasons, a modular approach improves resources use efficiency and fosters modelling unit higher quality (Donatelli and Rizzoli, 2008).

ESRC is a mechanistic, multi-year, multi-crop, daily time step SRC system simulation model derived from Cropping System Simulator (CSS) model structure (Danuso et al., 1999).

It is formed by a set of eight modules (*ESRC_soil*, *ESRC_SOM*, *ESRC_water*, *ESRC_nitrogen*, *ESRC_biomass*, *ESRC_management*, *ESRC_energy*, *ESRC_GHGB, TimeMangament*) connected by a main model file (*ESRC_main*). The modules (.smo name extension) and the model file (.sem) are text files in which every line completely describes a system entity.

Each module simulates a different domain of the whole system, instead *TimeManagement* module converts simulation time (progressive integer number) into calendar date.

ESRC executable model is created using SEMoLa platform through two steps: 1) SEMoLa code translation into Basic source code, which also involves the generation of template files for simulation and 2) Basic source code compilation into an executable, by an external compiler (Pbcc).

ESRC simulates SRC phenology and growth, soil water balance, organic matter and nitrogen dynamics and cropping practices effects. Management practices currently considered are: planting, irrigation, nitrogen fertilisation, and cutting event. Furthermore, *ESRC_Energy* module accounts for stand energy balance, considering both direct and indirect energy inputs, whereas the environmental module simulates greenhouse gases budget (GHGB) dynamics taking into account both C and N CO_2-eq emissions, on a farm scale, and estimates nitrogen leaching to the groundwater.

The simulation results generated by the model are: the aboveground (leaves and stems plus branches) and belowground biomass accumulation (coarse and fine roots), soil water dynamics, nitrogen and carbon dynamics and the energy and carbon balance of plantation, which are crucial aspects to evaluate the sustainability of energy crops. In following modules composing *ESRC* are introduced.

2.1. Soil module

The *ESRC_soil* module describes the physical characteristics of the soil.

It requires gravel content, soil clay content, saturated conductivity, wilting point, field water capacity and maximum water capacity, treated as model input parameters.

The module uses the two buckets representation to simulate soil dynamics (Coleman and Jenkinson, 1996) and soil depth is calculated as a function of the root deepening, synchronized to the epigeal development.

ESRC_soil also computes soil temperature and matric potential, which influence microbial and root activity and, consequently, soil respiration. Time step soil temperature changing is calculated as function of the difference between current mean air temperature and previous soil temperature and is based on heat transfer coefficient of the soil.

Matric potential is determined from air diffusion using the Campbell law (Campbell, 1974).

2.2. Soil organic matter module

ESRC_SOM simulates the dynamics of the organic matter (S*OM*) in the soil adopting the approach proposed in RothC by Coleman and Jenkinson (1996). Soil biomass is split into five compartments. Four of them are active stocks: decomposable plant material (*DPM*), resistant plant material (*RPM*), soil microorganism (*BIO*) and humus (*HUM*), whereas the last one is inert organic matter (*IOM*). The decay rates (*DecnDPM*, *DecnRPM*, *DecnBIO*, *DecnHUM*) of active organic matter pools (eq. 1 to 4) is equal to the active stock multiplied by the respective decomposition constant (Dr_{DPM}, Dr_{RPM}, Dr_{BIO}, Dr_{HUM}). Soil temperature, soil moisture and soil cover affect compartment decomposition rates on the basis of *DrT*, *DrM* and *DrCov* modifying factors respectively.

$$\frac{\mathrm{dDPM}}{\mathrm{dt}} = \mathrm{DecnDPM} = \mathrm{DPM} \cdot \mathrm{Dr_{DPM}} \cdot \mathrm{DrT} \cdot \mathrm{DrM} \cdot \mathrm{DrCov} \quad (1)$$

$$\frac{\mathrm{dRPM}}{\mathrm{dt}} = \mathrm{DecnRPM} = \mathrm{RPM} \cdot \mathrm{Dr_{RPM}} \cdot \mathrm{DrT} \cdot \mathrm{DrM} \cdot \mathrm{DrCov} \quad (2)$$

$$\frac{\mathrm{dBIO}}{\mathrm{dt}} = \mathrm{DecnBIO} = \mathrm{BIO} \cdot \mathrm{Dr_{BIO}} \cdot \mathrm{DrT} \cdot \mathrm{DrM} \cdot \mathrm{DrCov} \quad (3)$$

$$\frac{\mathrm{dHUM}}{\mathrm{dt}} = \mathrm{DecnHUM} = \mathrm{HUM} \cdot \mathrm{Dr_{HUM}} \cdot \mathrm{DrT} \cdot \mathrm{DrM} \cdot \mathrm{DrCov} \quad (4)$$

where decay rates are expressed in t of dry matter (DM) ha^{-1} d^{-1}, active stocks in t DM ha^{-1} and respective decomposition rate constant in d^{-1}. *DrT*, *DrM* and *DrCov* are dimensionless.

Active stock decomposition produces HUM and BIO and release CO_2. The redistribution of the just decomposed material to BIO, HUM and CO_2 is affected by clay content (*Clay*) according to the proportion:

$$\mathrm{ResDecr} = \frac{\mathrm{CO_2}}{\mathrm{BIO+HUM}} = \mathrm{scDec} \cdot \left(1.85 + 1.6\ \mathrm{e}^{(-0.0786\ \cdot \mathrm{Clay})}\right) \quad (5)$$

where *ResDecr* is dimensionless, *Clay* is expressed as % w/w on fine fraction and *scDec* is a dimensionless scaling factor equal to 1.67.

Hence, the CO_2 release rate (eq. 7), caused by time step decay of total organic matter (*TotDecn*), is equal to:

$$\mathrm{TotDecn} = \frac{\mathrm{dDPM}}{\mathrm{dt}} + \frac{\mathrm{dRPM}}{\mathrm{dt}} + \frac{\mathrm{dBIO}}{\mathrm{dt}} + \frac{\mathrm{dHUM}}{\mathrm{dt}} \quad (6)$$

$$\frac{\mathrm{dCO_2}}{\mathrm{dt}} = \mathrm{TotDecn} \cdot \frac{\mathrm{ResDecr}}{1+\mathrm{ResDecr}} \cdot \frac{44}{30} \quad (7)$$

where *TotDecn* is expressed as t DM ha^{-1} d^{-1}, dCO_2/dt is expressed as t ha^{-1} d^{-1} and 44/30 is the stoichiometric ratio between CO_2 and CH_2O.

The fraction of *TotDecn* transformed into *BIO* and *HUM* is:

$$\frac{\mathrm{d(BIO+HUM)}}{\mathrm{dt}} = \mathrm{TotDecn} \cdot \frac{1}{1+\mathrm{ResDecr}} \qquad (8)$$

where *d(BIO+HUM)/dt* is expressed as t DM ha^{-1} d^{-1}.

Finally, the repartition between BIO and HUM is performed according to BIO/HUM ratio defined as model constant.

2.3. Water module

Water balance is central to the growth strategy of any crop, even in moist soils. *ESRC_water* module carries out, with a mono layer cascade approach, the water balance of soil, providing simulations of soil water content, taking into account crop maximum (*ETm*) and actual (*Eta*) evapotranspiration, irrigation, infiltration, runoff, and drainage processes.

The maximum evapotranspiration is calculated as $ETm=Kc \cdot ET_0$, where *Kc* is the crop coefficient for the loss of water, according to the phenological stage (Allen *et al*., 1998) and ET_0 is the reference evapotranspiration in mm d^{-1}.

Crop actual evapotranspiration depends on the actual volumetric soil moisture (*SM*):

$$\mathrm{ETa} = \begin{cases} 0, & \mathrm{SM} < \mathrm{WPgrav} \\ \mathrm{Etm} \cdot \frac{\mathrm{SM-WPgrav}}{\mathrm{CM-WPgrav}}, & \mathrm{WPgrav} \leq \mathrm{SM} < \mathrm{CM} \\ \mathrm{ETm}, & \mathrm{SM} \geq \mathrm{CM} \end{cases} \qquad (9)$$

where *Eta* and *ETm* are in mm d^{-1}, *WPgrav* is the soil wilting point corrected for the volumetric gravel percentage in mm mm^{-1}, *SM is in* mm mm^{-1}, and *CM* is the critical soil moisture for crop stress in mm mm^{-1}, represented by the point when *Eta*/*ETm* starts to decrease reducing *SM*.

CM corresponds to the remaining water content in the root zone once that readily available water has been depleted (Allen et al., 1998):

$$\mathrm{CM} = \mathrm{FCgrav} - (\mathrm{FCgrav} - \mathrm{WPgrav}) \cdot [\mathrm{p}_{22} + 0.04 \cdot (5 - \mathrm{ETm})] \qquad (10)$$

where *FCgrav* is water field capacity corrected for volumetric gravel percentage in mm mm^{-1}, p_{22} is the soil water depletion dimensionless factor for no stress.

Soil water content increases with rainfall and irrigation. Water daily infiltration in the soil (*Infilt*) in mm d^{-1} is supposed equal to soil daily water supply (*WatSup*), when it is lower than soil saturated hydraulic conductivity (*Ks*) in mm d^{-1}, otherwise is equal to *Ks*. *WatSup* is represented by the sum of irrigation and rainfall in mm. Runoff is calculated as the difference between *WatSup* and *Infilt* if *WatSup*>*Ks*, otherwise is null. Drainage (*Drainage*) is the process that transfers water from the root layer to the deep soil layer, according to the two buckets representation. Drainage occurs when infiltration is greater than soil water deficit (*Deficit*) computed as:

$$\mathrm{Deficit} = \mathrm{Dsoil} \cdot (\mathrm{FCgrav} - \mathrm{SM}) \qquad (11)$$

where *Deficit* is in mm, *Dsoil* is the root layer depth in mm and *SM* is current soil moisture in mm mm^{-1}.

Drainage, expressed in mm d^{-1}, is evaluated as difference between *Infilt* and *Deficit*.

2.4. Nitrogen module

ESRC_nitrogen module comprises separate budgets for nitrate (NO_3^-) and ammonium (NH_4^+). Ammonium is considered as NH_4^+ in solution and adsorbed on soil colloids. Simulated processes include mineralisation, fertilisation, nitrification, denitrification, plant nitrate uptake, N run-off, and leaching into groundwater.

Nitrogen mineralisation (kg N ha^{-1} d^{-1}) is calculated as:

$$\mathrm{N_{mineralisation}} = (\mathrm{DecnDPM} + \mathrm{DecnRPM}) \cdot \mathrm{CRNC} + (\mathrm{DecnHUM} + \mathrm{DecnBIO}) \cdot \frac{\mathrm{CHUM}}{\mathrm{CNHUM}} \qquad (12)$$

where *CRNC* is the nitrogen content in crop residues in kg N t DM^{-1}, *CHUM* is the carbon content of humus in kg C kg^{-1} HUM, and *CNHUM* the C/N ratio of humus in kg C kg^{-1} N.

Nitrification (*Nitri*) and denitrification (*Denit*) rates are first order processes dependent on soil temperature and moisture, according to the formulae (Hansen et al., 1991):

$$\mathrm{Nitri} = \mathrm{NH_4s} \cdot \mathrm{Knitri} \cdot \mathrm{Ftd} \cdot \mathrm{Fmn} \qquad (13)$$

$$\mathrm{Denit} = \mathrm{NO_3} \cdot \mathrm{Kdenitmax} \cdot \mathrm{Ftd} \cdot \mathrm{Fmd} \qquad (14)$$

Where *Nitri* and *Denit* (kg N ha^{-1} d^{-1}), *NH_4s* is the N-NH_4^+ in soil solution (kg N-NH_4^+ha^{-1}), *NO_3* is the soil nitrogen amount in the nitrate form (kg N-NO_3 ha^{-1}), *Knitri* is the nitrification rate coefficient at standard conditions (d^{-1}), *Kdenitmax* is the coefficient of maximum denitrification with saturated soil at 10 °C (d^{-1}), *Ftd* is a response function for temperature, *Fmn* and *Fmd* are response functions for moisture in nitrif1ication and denitrification processes, respectively.

Plant nitrogen uptake (*Nuptake*, kg N ha^{-1} d^{-1}) depends on the optimal concentration of nitrogen in plant (*OptNconc*, kg N t DM^{-1}) when N-NO_3^- is not a limiting factor in soil, and is aimed at satisfying nitrogen request of new plant tissues and compensating previous deficit:

$$\mathrm{Nuptake} = \begin{cases} 1.05 \cdot [(\mathrm{GR} \cdot \mathrm{OptNconc}) + \mathrm{W} \cdot (\mathrm{OptNconc} - \mathrm{Nconc})], & \mathrm{OptNconc} > \mathrm{Nconc} \\ 1.05 \cdot [(\mathrm{GR} \cdot \mathrm{OptNconc}), & \mathrm{otherwise} \end{cases} \quad (15)$$

where *GR* is the daily plant growth rate (t DM ha^{-1} d^{-1}), *W* is the dry weight of plant biomass (t DM ha^{-1}), and *Nconc* the actual nitrogen concentration in the biomass (kg N t DM^{-1}). *GR* and *W* are computed in *ESRC_biomass* module.

Daily run-off of N-NH_4^+ (*NH4roff*, kg N-NH_4^+ ha^{-1} d^{-1}) and N-NO_3^- (*NO3roff*, kg N-NO_3^- ha^{-1} d^{-1}) are computed by multiplying the daily water surface run-off by N-NH_4^+ (*NH4conc*, kg N-NH_4^+ mm^{-1}) and N-NO_3^- (*NO3conc*, kg N-NO_3^- mm^{-1}) concentration in soil solution, respectively. The model assumes equal and homogeneous the nitrogen concentration in soil solution and run-off water.

Nitrogen leaching is calculated in the same way separately for N-NH_4^+ (*NH4leach*, kg N-NH_4^+ ha^{-1} d^{-1}) and N-NO_3^- (*NO3leach*, kg N-NO_3^- ha^{-1} d^{-1}), multiplying the eventual daily water drainage by N-NH_4^+ and N-NO_3^- concentration in soil solution.

2.5. Biomass module

ESRC_biomass module simulates three processes: plant phenology, carbohydrates assimilation and biomass partitioning, and root deepening. Crop parameters are specific for different crops, and provide values for dry matter conversion factors, carbon, nitrogen, and water use in phenological stages.

Crop life cycle is divided into four sequential phenological stages: rooting/early growth, vegetation, senescence, and maturity. The progress from one to another is based on daily accumulation of thermal time, or *GDD* (Growing Degree Days), obtained from the difference between air temperature and a base temperature. The achievement of a sum of GDD equal to *GDDstart* (°C) allows the move to the vegetation phase, the reaching of *GDDsen* (°C) degree lets leaf senescence begin and *GDDend* (°C) is the goal to get maturity. The phenological stage determines plant water use coefficient (*Kc*).

The model primarily simulates assimilated carbohydrates partitioning between above and belowground parts of the plant using the RUE efficiency approach (Monteith and Moss, 1977):

$$\mathrm{AGR} = \mathrm{GR} \cdot \mathrm{Fshoot} \qquad (16)$$

$$\mathrm{BGR} = \mathrm{GR} \cdot (1 - \mathrm{Fshoot}) \qquad (17)$$

where *AGR* (t DM ha^{-1} d^{-1}) are carbohydrates that daily moves to aboveground portion of the plant while *BGR* (t DM ha^{-1} d^{-1}) are those that arrive into the hypogeic part, *Fshoot* is the simulated fraction of carbohydrates that moves towards the epigeic fraction and *GR* is the daily growth rate. *GR* is given by:

$$\mathrm{GR} = \mathrm{IRad} \cdot \mathrm{RUE} \cdot \mathrm{Ft} \cdot \mathrm{Fws} \cdot \mathrm{FN} \cdot \left(\frac{\mathrm{Ksur}}{100}\right) \qquad (18)$$

where *IRad* is the daily light interception (MJ m^{-2} d^{-1}) function of leaf area index *LAI* (m^2 m^{-2}), *RUE* is the radiation use efficiency (g DM MJ^{-1}), *Ft*, *Fws* and *FN* are reduction dimensionless factors for temperature, water and nitrogen stress, respectively, computed with table functions as shown in Fig. 1 (assuming values from 0 to 1) and *Ksur* is the stump survival rate (%).

IRad is a fraction of the direct solar radiation (*Rg*, MJ m^{-2} d^{-1}) defined as:

$$\mathrm{IRad} = \mathrm{Rg} \times [1 - e^{(-\mathrm{Kext} \times \mathrm{LAI})}] \qquad (19)$$

where *Kext* is the light extinction coefficient and *Rg* the solar direct radiation.

LAI is proportional to the leaves biomass (*WL*, t DM ha^{-1}) according to the formula:

$$\mathrm{LAI} = \mathrm{WL} \times \mathrm{SLA} \qquad (20)$$

where *SLA* is the specie-specific leaves area (m^2 m^{-2}).

In the time step consecutive to carbohydrates partitioning, the model computes dry biomass daily accumulation (t ha^{-1} d^{-1}) for four distinct states: stems (*WS*, t ha^{-1}), leaves (*WL*, t ha^{-1}), coarse (*WRc*, t ha^{-1}) and fine roots (*WRf*, t ha^{-1}). Fine roots distinction from the coarse ones allows to reliably estimate soil organic matter turnover in the short term. Fine roots emerge, die, and decompose in the soil continuously, thus having an annual turnover which may contribute to 20-70% of the total net primary production. Indeed, coarse roots of willows and poplars do not end their vitality at the end of a year, but produce for the entire productive cycle of SRC (Block *et al*., 2006; Rytter, 2012).

Total dry biomass (*W*, t ha^{-1}) decrease rate at cutting event is equal to:

$$\frac{\mathrm{dW}}{\mathrm{dt}} = \mathrm{HI} \cdot \mathrm{WS} \qquad (21)$$

where *HI* is the harvest index, and *WS* the cumulative stem biomass (t DM ha^{-1}).

The model considers plant resilience driving individuals to reach and to maintain a target value for the ratio between above and belowground biomass (ABr_T) substantially equal to the ratio commonly shown by a full-grown plant. ABr_T is calculated as $Fshoot_T$/(1-$Fshoot_T$) where $Fshoot_T$ is a model parameter derived from literature, representing the fraction of aboveground biomass in a plant.

In case of a gap during simulation between the current above/belowground biomass ratio (*ABr*), computed as (*WS*+*WL*)/(*WRc*+*WRf*), and ABr_T, the model counterbalances this perturbation modifying the partitioning of assimilated carbohydrates distribution between epigeic and hypogeic portion of the plant in order to favour the part in fault. This occurs mainly after defoliation or during the plant development period following a cut (Landhäusser and Lieffers, 2002; 2003).

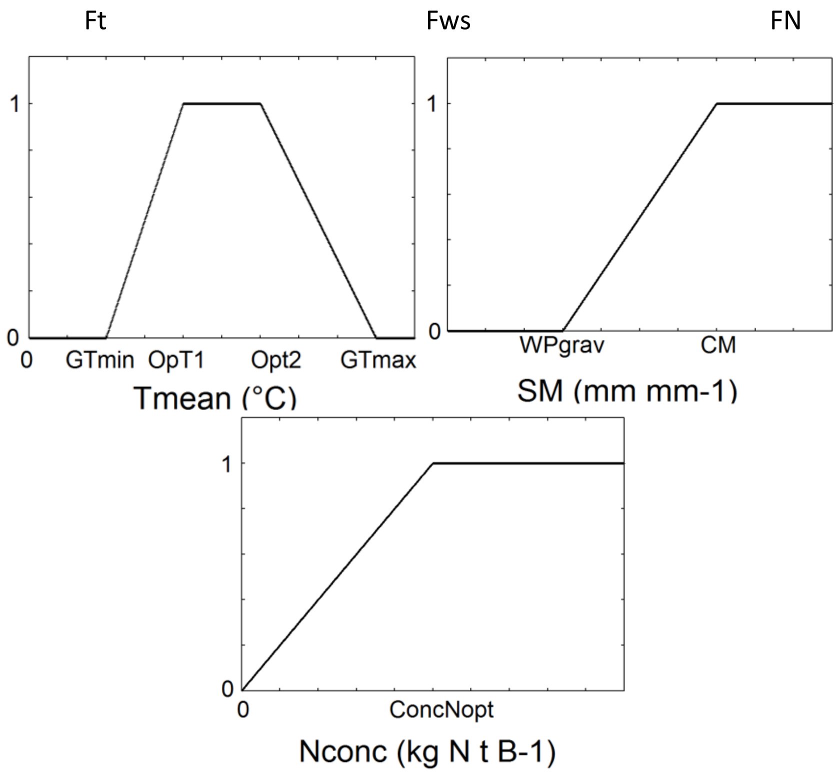


Fig. 1. Temperature (*Ft*), water stress (*Fws*) and nitrogen (*FN*) growth reduction factor. *Tmean*: daily air mean temperature (°C); *GTmin*: species-specific air base temperature for degree accumulation (°C); *GTmax*: maximum air temperature for growth (°C); *Opt1* and *OpT2*: minimum and maximum optimal growth air temperature (°C); *SM*: volumetric soil moisture; *WPgrav*: soil wilting point corrected for the gravel content; *CM*: critical soil moisture; *OptNconc*: optimal nitrogen plant concentration; *Nconc*: nitrogen biomass concentration.

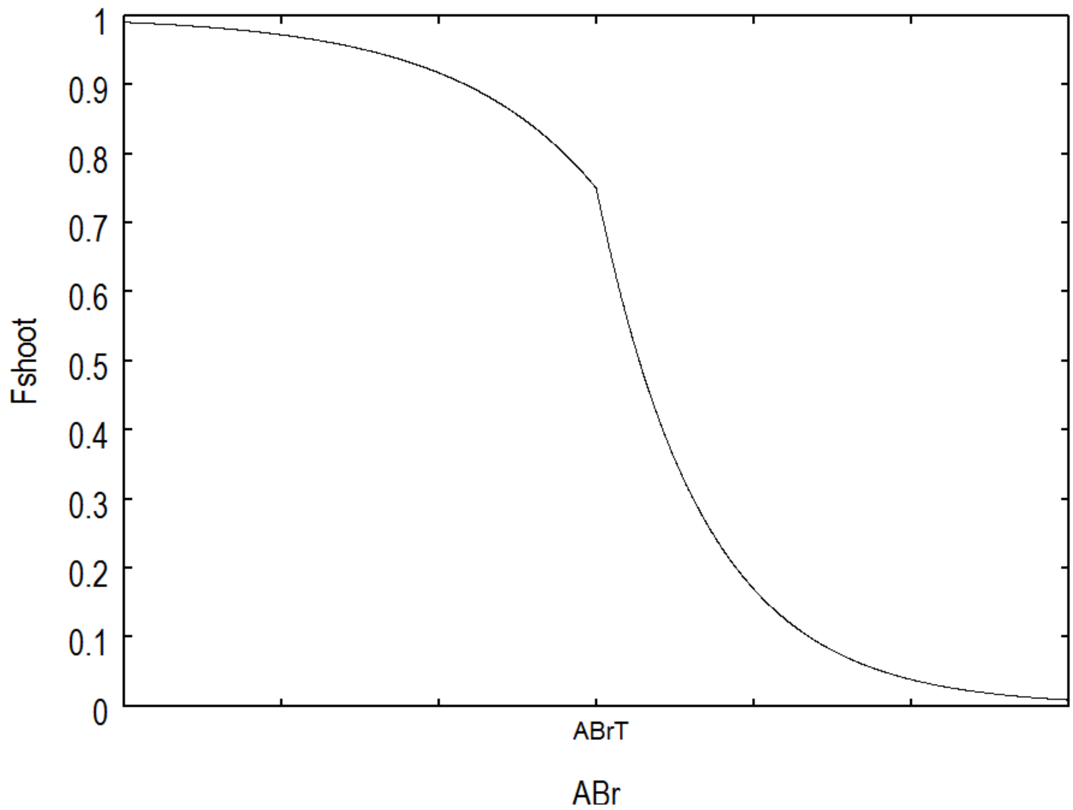


Fig. 2. Fraction of assimilated carbohydrates moving to the aboveground portion of a SRC plant (*Fshoot*) as a function of the current above belowground biomass ratio (*ABr*). *ABrT* is the target value for the ratio between above and belowground biomass, equal to the ratio commonly shown by a full-grown plant.

Therefore, *Fshoot* is computed in runtime using a sigmoid function of *ABr* (Fig. 2):

$$\mathrm{Fshoot} = \begin{cases} 1 - e^{\left(\frac{\log(100-100\cdot \mathrm{Fshoot_T})}{\mathrm{ABr_T}-0.1}\cdot \mathrm{ABr}\right)} \cdot e^{\left(-\frac{\log(100-100\cdot \mathrm{Fshoot_T})}{\mathrm{ABr_T}-0.1}\cdot 0.1\right)} \cdot 0.01, & \mathrm{ABr} \leq \mathrm{ABr_T} \\ e^{\left(-\frac{\log(100\cdot \mathrm{Fshoot_T})}{\mathrm{ABr_T}-0.1}\cdot \mathrm{ABr}\right)} \cdot e^{\left(\frac{\log(100\cdot \mathrm{Fshoot_T})}{\mathrm{ABr_T}-0.1}\cdot \mathrm{ABr_T}\right)} \cdot \mathrm{Fshoot_T}, & \text{otherwise} \end{cases}$$

(22)

The function is considered in the range $0 \leq ABr \leq +\infty$ and *Fshoot* value ranges between 0 and 1. *Fshoot* assumes value equal to 0.99 when *ABr*=0.1 and 0.01 when *ABr*=2ABr_T-0.1.

The function presents substantially two kinds of behaviours: there is an exponential answer for small gaps from the inflection point which becomes more and more asymptotic getting close to the function bounds.

Model simulates the daily translocation of carbohydrates reserves from roots to shoots during the sprouting (*CarboTrans*, t DM ha^{-1} d^{-1}):

$$\mathrm{CarboTrans} = \mathrm{WB} \cdot \mathrm{Fshoot} \qquad (23)$$

where *WB* is the carbohydrates reserve in roots (t DM ha^{-1}).

Cutting frequency influences stand productivity, likely due to the effects occurring after coppicing like decrease in aboveground growth (Heilman and Peabody, 1981) and increased stool mortality (Koop et al., 2001; Labrecque and Teodorescu, 2005). *ESRC* dynamically estimates the stump survival rate (*Ksur*) using a function calibrated on data reported by Nassi o Di Nasso et al. (2010) (Fig. 3). The paper shows the *Ksur* dynamics over time for three plantations of *Populus deltoides* Bartr. (clone Lux) with different cutting cycle (1, 2 and 3 years). For a given cutting cycle length (*CC*, yr) there is a linear function that links *Ksur* to the plantation age (*Age*, yr):

$$\mathrm{Ksur} = \mathrm{IniSur} - \mathrm{KsurDecRate} \cdot \mathrm{Age} \qquad (24)$$

where *IniSur* is the initial stump survival rate expressed as a percentage, likely plant genotype-dependent (Ceulemans and Deraedt, 1999), and *KsurDecRate* is the ageing rate equivalent to the *Ksur* decreasing speed (yr^{-1}). The paper also shows that increasing cutting frequency, stump survival rate decreases more rapidly over time. It has been supposed that *KsurDecRate* parameter is an exponential function of the *CC*:

$$\mathrm{KsurDecRate} = \mathrm{MaxKsurDecRate} \cdot e^{-\mathrm{CS} \cdot \mathrm{CC}} \qquad (25)$$

where *MaxKsurDecRate* is the potential maximum value of *KsurDecRate* (yr^{-1}), corresponding to a theoretical cutting cycle of null length and *CS* is the sensitivity to cut (yr^{-1}). *MaxKsurDecRate* assumes values ≥ 0 and the more it is higher, the more the clone is sensitive to the highest cutting frequencies. *CS* assumes values ≥ 0 and the more it is higher, the more the clone decreases the sensitivity to cut, independently from cutting cycle. *IniSur*, $MaxKsurDecRate$ and *CS* are model parameters that remain constant over simulation time, while the model takes into account changes of *CC* over time. *Ksur* is set equal to *IniSur* at simulation start time and is then re-calculated at

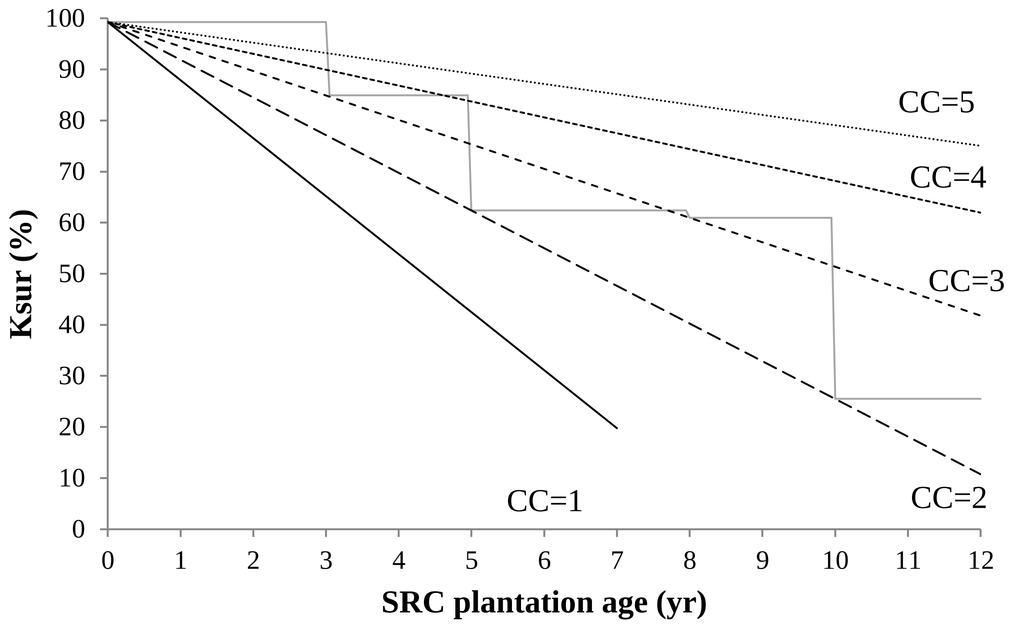


Fig. 3 Stump survival rate (*Ksur*) as a function of plantation age for different cutting cycles (CC, 1 to 5 years) (eq. 24; black lines). The origin of x-axis represents the stand establishment time. *Ksur* has been also computed in runtime in the simulation of a 12-year-old SRC poplar stand with variable rotation length (cutting events after 3, 5, 8 and 10 years from the stand establishment, grey step line). Function parameters have been derived from Nassi o di Nasso et al. (2010): *IniSur*=99.27%, *MaxKsurDecRate*=17.5 yr^{-1}, *CS*=0.432 yr^{-1}.

every cutting event, on the basis of the plantation age and of the elapsed time from the previous cutting event. Fig. 3 shows *Ksur* function for different cutting cycles, from 1 to 5 years, over a period of 12 years. It has been also presented, only for illustrative purpose, *Ksur* day-by-day estimation for a hypothetical plantation of poplar with cutting events scheduled after 3, 5, 8 and 10 years from the stand establishment date.

The nutrient status of plants is largely determined by root system development, governing extraction of nutrients from soil. The root deepening per day (*IncRoot*, mm d^{-1}) is calculated as:

$$\mathrm{IncRoot} = \mathrm{Rmax} \times \frac{\mathrm{Tmean} - \mathrm{GTmin}}{[1 + (\frac{\mathrm{GDD}}{\mathrm{GDDend}})^{20}]} \quad (26)$$

where *Rmax* is the daily maximum value of deepening (mm d^{-1}), *Tmean* is the daily air mean temperature, and *GTmin* is the species-specific air base temperature for degree accumulation (°C).

2.6. Management module

ESRC_management simulates cropping practices (planting, irrigation, fertilisation and cut) as events scheduled by user who sets timing and any amounts. Fertilisation and irrigation events can be automatically generated using an internal decisional strategy arising from information provided by other modules (temperature, phenological stage, water and nutritional stress index, etc,).

Automatic planting is based on mean air temperature values: when the daily mean temperature is greater than the plant base temperature for more than 3 consecutive days, the cuttings will be planted.

As regards automatic irrigation, the computation of the soil moisture level to trigger an irrigation event (*AIM*, mm) requires the user to establish an accepted water stress level for the plant (*Kw*):

$$\mathrm{AIM} = \mathrm{WPgrav} + (\mathrm{CM} - \mathrm{WPgrav}) \cdot (1 - \mathrm{Kw}) \quad (27)$$

where, as aforementioned, *WPgrav* is the soil wilting point corrected for the gravel content and *CM* the soil moisture when the crop stress starts. When the actual soil moisture (*SM*) becomes smaller than *AIM*, the irrigation will be performed. Increasing *Kw*, the number of irrigation events decrease as well as *AIM*. The automatic irrigation water volume (*IrriVol*, mm) is calculated as the amount of water needed to bring the soil moisture back to field capacity for the current soil rooting depth:

$$\mathrm{IrriVol} = \frac{\mathrm{Deficit}}{\mathrm{IrriEff}} \quad (28)$$

where *IrriEff* is the irrigation efficiency parameter.

The automatic N fertilisation adopts the same criteria of the automatic irrigation: a parameter of acceptable nutritional stress (*KN)* is used. When *FN* is smaller than *KN* the automatic fertilisation is performed. The amount of applied nitrogen fertiliser is defined by a user-defined parameter (*AutoNFert*, kg N ha^{-1}). Both automatic irrigation and fertilisation allow the crop to grow without stress, providing the maximum biomass accumulation, depending on temperature and radiation regimes.

2.7. Energy module

Agricultural practices bring about energy costs for farm. Agricultural support energy arises from primary, secondary and tertiary sources according to Gifford et al. (1984). Primary support energy is used directly as fuel and power on the field. Secondary support energy is that required to manufacture consumable inputs to plant and animal growth (fertilizer, biocides, pharmaceuticals) Tertiary support energy is used in manufacturing plant and equipment for use on the farm. *ESRC_energy* accounts both for direct and indirect energy input, applying an LCA (Life Cycle Assessment) approach (Brentrup *et al.*, 2001; Brentrup *et al.*, 2004). Initial module parameters are set on values reported in Ecoinvent database 2.2 (Ecoinvent, 2010).

Energy gains (*PlantEnOut*, GJ ha^{-1}) are associated to the energy embodied in plant molecules, roughly estimated multiplying biomass production by its low heating value.

Operation practices (*Oper*: planting, irrigation, nitrogen mineral fertilisation and harvest) are simulated as discrete events, as the relative energy costs they lead to are accounted. Module distinguishes among primary, secondary and tertiary energy expenses for operations.

Primary energy, linked to direct fuel and power consumption (*OperDirEnPr*, MJ ha^{-1}), is generally estimated as:

$$\mathrm{OperDirEnPr} = \mathrm{FuelEn} \cdot \mathrm{OperFuelCon} + \mathrm{LubEn} \cdot \mathrm{OperLubCon} \quad (29)$$

where *FuelEn* is the energy cost for refining and distributing a kg of diesel (MJ kg^{-1}), *OperFuelCon* is the operation fuel consumption (MJ ha^{-1}), *LubEn* is the energy for producing a kg of lubricant oil, and *OperLubCon* its consumption for the agricultural practice.

The indirect energy cost associated to the consumption of a generic consumable input (*ProdIndEnSec*, MJ kg^{-1}), such as fertilisers and saplings, is calculated as:

$$\mathrm{ProdIndEnSec} = \mathrm{ProdEn} \cdot \mathrm{ProdWeight} \quad (30)$$

where *ProdEn* is the energy necessary for manufacturing the product (MJ kg^{-1}) and *ProdWeight* the used amount (kg).

Tertiary support energy (*OperIndEnTer*, MJ ha^{-1}), used in manufacturing plant and equipment for use in the farm, is computed as:

$$\mathrm{OperIndEnTer} = \mathrm{TracEn} \cdot \mathrm{TracWeight} \cdot \frac{\mathrm{OperTime}}{\mathrm{TracLife}} + \mathrm{MacEn} \cdot \mathrm{OperWeight} \cdot \frac{\mathrm{OperTime}}{\mathrm{OperLife}} \qquad (31)$$

where *TracEn* is the energy to produce, maintain, repair and dispose a kg of tractor (MJ kg^{-1}), *TracWeight* is the tractor mass (kg), *OperTime* is the time required for the operation (h ha^{-1}), *TracLife* is the useful life of tractor (h), *MacEn* is the average energy to produce, maintain, repair and dispose a kg of agricultural tillage machinery (MJ kg^{-1}) and *OperWeight* is the mass of the machine in use (kg).

Plantation energy balance derives from the difference between *PlantEnOut* and the sum of direct (*OperDirEnPr*) and indirect energy inputs (*ProdIndEnSec*, *OperIndEnTer*).

2.8. GHGB module

Agriculture contributes to the emission of greenhouse gases (GHGs) through disturbance of soil and vegetation carbon pools (e.g. ploughing/tillage and management of crop residues) and the biospheric fluxes of other GHGs, but also through field or farm operations (e.g. emission of fossil fuels from energy sources needed for tillage practices or in the application of organic amendments and chemicals) (Ceschia et al., 2010).

A complete description of all ecosystem C-eq fluxes is really expensive in terms of field measurements (Smith et al., 2010). Moreover, it is often no longer obtainable from already concluded survey data collection.

ESRC_GHGB uses a micrometeorological approach to dynamically estimate the components of the ecosystem greenhouse gas budget (GHGB): positive fluxes leave the ecosystem and represent carbon losses, conversely negative ones are uptakes (e.g. carbon fixing) and constitute carbon gains.

GHGB is a cumulative variable computed in runtime from the stand establishment date till the last cutting event.

The module computes daily Net Primary Productivity (NPP, t C ha^{-1} $cycle^{-1}$), the quantity of photosynthates not used for plant respiration and available for other processes and heterotrophic respiration (RH, t C ha^{-1} $cycle^{-1}$), which derives from the decomposition of biomass in the current plant cycle but also from the organic matter accumulated in the ecosystem over time. This allows to estimate cumulated Net Ecosystem Productivity (NEP, t C ha^{-1} $cycle^{-1}$), calculated as the difference between the NPP and RH, and Net Biome Productivity (NBP, t C ha^{-1} $cycle^{-1}$) that explicitly takes into account C fluxes caused by disturbance (harvest, organic fertilisers):

$$\mathrm{NBP} = \mathrm{NEP} + \mathrm{Cexp} + \mathrm{OF} + \mathrm{S} \qquad (32)$$

where *Cexp* (t C ha^{-1}) is the carbon exported from the field during harvest, *OF* is the carbon imported with organic fertilisation (t C ha^{-1}) and *S* are the C gains with the saplings (t C ha^{-1}).

The GHGB (t C-eq ha^{-1} $cycle^{-1}$), based on farm scale, includes N_2O, CH_4 and CO_2 emissions arising from field operations (*EFO*, t C ha^{-1} $cycle^{-1}$), to which have been respectively associated global warming potentials of 298, 25 and 1 (relative to an equivalent mass of CO_2) assuming a 100-yr time horizon (Forster et al., 2007):

$$\mathrm{GHGB} = \mathrm{NBP} + \sum \mathrm{EFO} \qquad (33)$$

Field operations were sorted into primary, secondary and tertiary sources of C or GHGs according Gifford et al. (1984). Emissions were converted to C equivalents (C-eq) using a carbon to CO_2 mass ratio of 0.2727:

3. *ESRC* data requirements and use

Template files are text files written in a simplified form of Stata dictionary file format (.dct) (StataCorp., 1985). Users, to perform a simulation, have to prepare: a) the simulation file, to set the simulation; b) the parameter file, declaring model parameters; c) the event file, which schedules model events and d) related action files; e) the exogenous file containing the required exogenous variables. Files can be created editing template files generated by SEMoLa during model building or using facilities of SEMoLa platform.

Parfile contains values used to initialize model parameters at the beginning of simulation (soil, crop and management parameters). Parameter values remain constant for all simulation steps; however, occurrences of internal or external events can modify current parameter values during simulation. Every data row in *parfile* (*parset*) is a complete parameter set for the model, identified by a parset code (*pcode*, first variable of the row).

Information about parameters and their sources of information are reported in Table 2.

Exogenous variables (*exovar*) contain information outside system, not under its control but affecting its behaviour. Exovar data have to be available for each simulation step. *ESRC exofile* must contain six variables: exodata set code (*ecode*), time (*Time*, d), maximum and minimum temperature (*Tmax* and *Tmin*, °C), rainfall (*Rain*, mm), global radiation (*Rg*, MJ m^{-2}) and reference evapotranspiration. *ecode* allows to distinguish between different *exosets* in a exofile, for instance, pertaining to different years or locations.

The model treats agricultural practices (planting, mineral fertilisation, irrigation, cut) like external events which occur instantaneously at scheduled time step and modify system state or parameters. External events occurrences are declared in *evtfile*. A single event is defined by a code (*vcode*), the time and the kind of the event and an *acode* referring to a parameter set in an *actfile* that must substitute their current values in the model on the specific event. There is an actfile for each kind of event (e.g. planting.act), containing different parameter sets identified by different acode (*actsets*). *Actsets* represent different operation methods for the same agricultural practice.

Simulation file (*simfile*) contains all the information needed to run a simulation. *Simfile* header includes different extended header items to give information on how to customize simulation.

It is possible to perform different kind of simulations combining in a different way the available sets of parameter, events and exogenous data to create different *simsets* and also launch multiple simulations, in which every row of *simfile* correspond to a single simulation.

ESRC SEMola code can be compiled and run from SEMola platform whereas the executable model (*ESRC*.exe) can be launched from the console window or shelled from other applications, running as stand-alone software. In every case the model run requires only its own SEMoLa library DLL created during model building.

The complete list of commands to launch, calibrate and validate *ESRC* executable model is reported in Appendix A or can be obtained calling the console application help in DOS environment by the command:{wf}\ESRC help, where :{wf} is the folder containing the *ESRC* executable file.

Model documentation, update model modules, example files for simulation and a model help can be freely downloadable.

Table 2. Information on model parameters separated by modules.

Parameter	Default value and range	Unit	Description	Parameter type[a]	Reference[b]
TimeManagement					
StartYear	-	-	First simulation year	S	UC
ESRC_soil					
Clay	-	% w/w on fine fraction	Soil clay content	C	SD
DsMax	-	mm	Maximum rootable soil depth	C	SD
Dw	-	mm	Tillage depth	O	MC
FC	-	mm mm^{-1}	Soil water field capacity	C	SD
Grav	-	%	Gravel volumetric content	C	SD
IniNH4	-	kg N ha^{-1}	Soil initial N-NH_4^+ content	O	SD
IniNO3	-	kg N ha^{-1}	Soil initial N-NO_3^- content	S	SD
IniSOM	-	%	Soil organic matter	C	SD
Knitri	0.7	-	Nitrification coefficient	C	A
Ks	-	mm d^{-1}	Soil saturated conductivity	C	SD
MWC	-	mm mm^{-1}	Maximum soil water capacity	C	SD
WP	-	mm mm^{-1}	Soil wilting point	C	SD

ESRC_water					
IniSM0	0.1	mm mm^{-1}	Initial soil moisture	S	SD
ESRC_nitrogen					
OptNconc	5 (1-50)	kg N Mg^{-1}	Optimal N concentration in biomass	C	Derived from Eckersten and Slapokas, 1990
ESRC_biomass					
CRNC	0.0075	kg N kg^{-1}	Crop residues N content	S	Experimental result
CS	0.432	yr^{-1}	Sensitivity to cut	C	Derived from Nassi o di Nasso et al., 2010
DPMfrac	0.2	-	Fraction of DPM in plant residues	C	Coleman and Jenkinson, 1996
Ffroots	0.3	-	Fraction of fine roots in roots	C	Garten et al., 2011
FShootT	0.75 (0.66-0.92)	-	Fraction of aboveground biomass (target)	C	Default value derived from Grogan and Matthews, 2001; Range: poplar 0.71 (Garten et al., 2011)-0.90 (Swamy et al., 2006); willow 0.66-0.92 (Stadnyk, 2010)
Fstem	0.85 (0.59-0.95)	-	Fraction of stems in aboveground biomass	C	Derived from Proe et al., 2002
GDDend	2800	°C	GDD beginning of full senescence	C	A
GDDsen	2700	°C	GDD beginning of leaf senescence	C	A
GDDstart	227	°C	GDD for starting vegetation	C	A
GTmax	40	°C	Growth maximum temperature	C	Amichev et al., 2010
GTmin	5	°C	Growth minimum temperature	C	Eckersten and Slapokas, 1990
HI	0.9	-	Harvest index	C	Verwijst, 1991
IniNcrop	20	kg N ha^{-1}	Initial amount of N in plant shoots	S	Experimental result
IniSur	99.27	%	Initial stump survival rate	C	Derived from Nassi o di Nasso et al., 2010
InitialW	-	Mg ha^{-1}	Initial biomass at planting	S	MC
Kc1	0.1 (0-1)	-	Kc at planting	C	Allen et al., 1998; Guidi et al., 2008
Kc2	0.5 (0.2-1.2)	-	Kc at the start of vegetative phase	C	Allen et al., 1998; Guidi et al., 2008
Kc3	1.4 (0.8-1.6)	-	Kc at the start of senescence	C	Allen et al., 1998; Guidi et al., 2008
Kc4	0.3 (0-1)	-	Kc at full senescence	C	Allen et al., 1998; Guidi et al., 2008
KdeadS	0.22	-	Coefficient of dead shoots	C	A
Kdec	0.09	d^{-1}	Leaf senescence coefficient	C	A
Kext	0.5 (0.4-0.7)	-	Light extinction coefficient	C	Cannell et al., 1987
MaxDecSurRate	17.5	yr^{-1}	Potential maximum survival decrease rate	C	Derived from Nassi o di Nasso et al., 2010
OpT1	20	°C	Lower optimum temperature for growth	C	Amichev et al., 2010
OpT2	25	°C	Upper optimum temperature for growth	C	A
p22	0.4	-	Soil water depletion fraction for no stress	C	Derived from Allen et al., 1998
Rmax	0.25	mm d^{-1}	Maximum root deepening rate	C	A

RPMfrac	0.8	-	Fraction of RPM in plant residues	C	Coleman and Jenkinson, 1996
RUE	1.7 (1.3-1.9)	g MJ^{-1}	Radiation use efficiency	C	Derived from Kiniry, 1998
SLA	2.2 (1.5-4)	ha Mg^{-1}	Specific leaf area	C	Mamashita et al., 2011. Range: poplar 1.5-4; willow 1.5-2
TTCR	5	yr	Turnover time of live coarse roots	C	Garten et al., 2011
TTFR	1.3	yr	Turnover time of live fine roots	C	Garten et al., 2011
ESRC_manag	0				
AutoNfert	0	kg N	N fertilisation amount (automatic)	O	UC
IrriEff	0.9	-	Irrigation efficiency	S	MC
IrriType	1	-	Irrigation type: 1=scheduled, 2=automatic	S	UC
IrriVolSched	-	mm	Irrigation volume (scheduled)	O	MC
KN	0.4	-	N stress coefficient (accepted by farmer)	C	UC
Kw	0.4	-	Critical fraction of available water for stress (accepted by farmer)	C	UC
NFertType	1	-	Fertilisation type: 1=scheduled, 2=automatic	S	UC
SchedNH4Fert	-	kg N	N-NH_4^+ fertilisation amount (scheduled)	O	MC (physiological recommendation: 30-80 kg N ha^{-1} yr^{-1}, Sennerby-Forsse, 1995)
SchedNO3Fert	-	kg N	N-NO_3^- fertilisation amount (scheduled)	O	MC
ESRC_Energy					
ECleav	18500	MJ Mg^{-1}	Energy content of leaves	S	Nassi o di Nasso et al., 2010
ECrootC	18500	MJ Mg^{-1}	Energy content of coarse roots	S	Nassi o di Nasso et al., 2010
ECrootF	18500	MJ Mg^{-1}	Energy content of fine roots	S	Nassi o di Nasso et al., 2010
ECstem	18500	MJ Mg^{-1}	Energy content of stems	S	Nassi o di Nasso et al., 2010
FuelEn	54.6	MJ kg^{-1}	Energy to produce and distribute a kg of fuel	S	Ecoinvent, 2010
HarvFuelCon	51.02	kg ha^{-1}	Harvest fuel consumption	S	Guo et al., in press
HarvLife	11520	h	Useful life of the harvester	S	Experimental result
HarvLubCon	0.25	kg ha^{-1}	Harvest lubricant oil consumption	S	Experimental result
HarvTime	1.5	h ha^{-1}	Required time for harvest	S	Spinelli et al., 2006
HarvWeight	11000	kg	Harvester mass	S	Experimental result
IrriLife	1200	h	Useful life of the irrigation system	S	Experimental result
IrriTime	6.5	h ha^{-1}	Required time for irrigation	S	Experimental result
IrriWeight	800	kg	Irrigation system mass	S	Experimental result
LubEn	79.8	MJ kg^{-1}	Energy to produce a kg of lubricant oil	S	Ecoinvent, 2010
MacEn	83.2	MJ kg^{-1}	Energy to produce, maintain, repair and dispose a kg of agricultural tillage machinery	S	Ecoinvent, 2010

ModIrri	1	-	Irrigation method: 1=Flooding/furrow, 2=Sprinkler, 3=Rainger, 4=Hose reel irrigator, 5=Dripping	S	MC
NFertEn	66.3	MJ kg^{-1}	Energy to produce a kg of N (urea 46 %)	S	Ecoinvent, 2010
NFertFuelCon	0.55	kg ha^{-1}	Mineral fertilisation fuel consumption	S	Experimental result
NFertLife	1200	h ha^{-1}	Useful life of the mineral fertiliser spreader	S	Experimental result
NFertLubCon	0.025	kg ha^{-1}	Lubricant oil consumption of the mineral fertilisation	S	Experimental result
NFertTime	0.12	h	Required time for mineral fertilisation	S	Experimental result
NFertWeight	1620	kg	Mass of the mineral fertiliser spreader	S	Experimental result
PlantFuelCon	8.76	kg ha^{-1}	Planting fuel consumption	S	Guo et al., in press
PlantLife	3200	h	Useful life of the planter	S	Experimental result
PlantLubCon	0.3	kg ha^{-1}	Lubricant oil consumption of the planting	S	Experimental result
PlantTime	5	h ha^{-1}	Required time for planting	S	Manzone et al., 2006
PlantWeight	700	kg	Planter mass	S	Manzone et al., 2006
SapEn	0.725	MJ kg^{-1}	Energy to produce a kg DM of saplings	S	Huang, 2007
TracEn	132	MJ kg^{-1}	Energy to produce, maintain, repair and dispose a kg of tractor	S	Ecoinvent, 2010
TracLife	11200	h	Useful life of the tractor	S	Experimental result
TracWeight	4350	kg	Tractor mass	S	Experimental result
TrailLife	28800	h	Useful life of the trailer	S	Experimental result
TrailWeight	1500	kg	Trailer mass	S	Experimental result
ESRC_GHGB					
CH4toCO2eq	25	kg CO_2-eq kg CH_4^{-1}	Global warming potential 100-yr CH_4	S	Forster et al., 2007
CO2DirFuel	3.148	kg CO_2-eq kg^{-1}	CO_2-eq emission from diesel burning	S	Romano et al., 2014[c]
CO2IndFuel	0.508	kg CO_2-eq kg^{-1}	CO_2-eq emission to produce and distribute a kg of fuel	S	Ecoinvent, 2010
CO2IndLub	1.04	kg CO_2-eq kg^{-1}	CO_2-eq emission to produce a kg of lubricant oil	S	Ecoinvent, 2010
CO2Mac	4.42	kg CO_2-eq kg^{-1}	CO_2-eq emission to produce, maintain, repair and dispose a kg of agricultural tillage machinery	S	Ecoinvent, 2010
CO2NMin	3.29	kg CO_2-eq kg^{-1}	CO_2-eq emission to produce a kg of N (urea 46 %)	S	Ecoinvent, 2010
CO2Sap	0.014	kg CO_2-eq kg^{-1}	CO_2-eq emission to produce 1 kg DM of saplings	S	Huang, 2007
CO2Trac	6.05	kg CO_2-eq kg^{-1}	CO_2-eq emission to produce, maintain, repair and dispose a kg of tractor	S	Ecoinvent, 2010

EF1	0.01	kg N-N_2O kg N^{-1}	Emission factor for N_2O emissions from N inputs	S	IPCC, 2006
EFCH4	0.01	kg CH_4 kg N^{-1}	Emission factor for CH_4 from N fertilisation	S	Delucchi and Lipman, 2003
N2OtoCO2eq	298	kg CO_2-eq kg N_2O^{-1}	Global warming potential 100-yr N_2O	S	Forster et al., 2007

[a] S: Constant; C: Calibrable parameter; O: Optimizable parameter

[b] A: assumed; UC: model user choice: MC: management choice; SD: site-dependent

[c] paper reports kg CO_2 kg fuel^{-1}

4. Material and methods

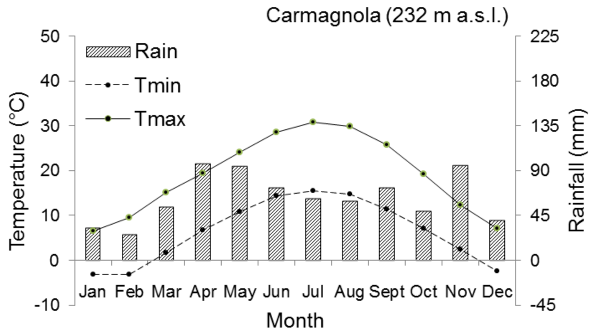
4.1. Field trials

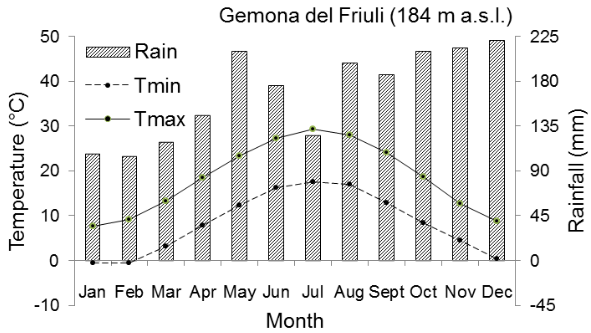
Field experiments were carried out in two locations (Osoppo and Lombriasco) in North-Eastern and North-Western Italy respectively (Table 3).

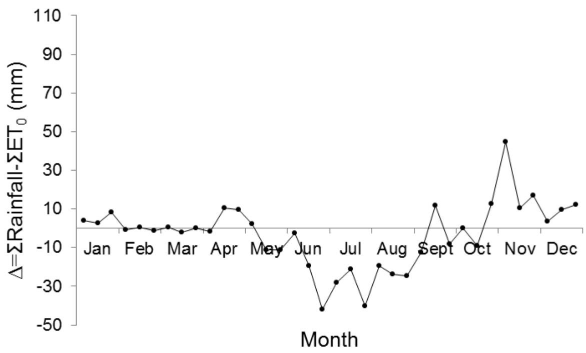
Meteorological daily data of *Tmin*, *Tmax*, *Rain* and *Rg* were obtained from weather stations near experimental sites. Lombriasco refers to the meteorological series of Carmagnola (acronym *LomC*, 44°53'' N, 7°41' E, from 1/1/2004 to 31/12/2013) while Osoppo climate is well represented by meteorological data of Gemona del Friuli (acronym *OsC* , 46°26' N, 13°12' E, from 1/1/2003 to 31/12/2010). Reference evapotranspiration was calculated using Penman-Monteith equation (Monteith, 1965). The climatic conditions at experimental sites are typical of the temperate environment (Fig. 4, Köppen and Geiger, 1936) with minimum temperatures just below 0 °C in winter and maximum temperatures above 35 °C in the summer. Total annual rainfall in Osoppo are roughly three times those in Lombriasco (2018 vs 752 mm).

Table 3. Experimental trials.

Exp. No.	Location	Latitude, Longitude, Altitude (m)	Period	Species	Clone	Density (plants ha^{-1})	Planting date	Fertilisation dates	Cutting dates	Replica-tes	Allometric analysis
1	Lombriasco	44°50' N, 7°38' E, 241 m a.s.l.	2004-2013	Poplar	I-214	5747	30/03/2004	-	30/01/2007 30/01/2009 30/01/2012 31/12/2013	3	January, 30th of 2005, 2006, 2007, 2008, 2009, 2011,
2	Lombriasco	44°50' N, 7°38' E, 241 m a.s.l.	2004-2013	Poplar	Orion	5747	30/03/2004	-	30/01/2007 30/01/2009 30/01/2012 31/12/2013	3	January, 30th of 2005, 2006, 2007, 2008, 2009, 2011,
3	Lombriasco	44°50' N, 7°38' E, 241 m a.s.l	2004-2013	Willow	Levante	5747	30/03/2004	-	30/01/2007 30/01/2009 30/01/2012 31/12/2013	3	January, 30th of 2005, 2006, 2007, 2008, 2009, 2011,
4	Osoppo	46°14' N, 13°5' E, 184 m a.s.l.	2003-2010	Poplar	I-214	6173	01/01/2003	01/01/2003 100 kg N 31/12/2003 50 kg N 31/12/2004 50 kg N	30/11/2004 30/11/2006 30/11/2010	4	November 30th of 2004, 2006 2007, 2008
5	Osoppo	46°14' N, 13°5' E, 184 m a.s.l	2003-2010	Poplar	Orion	6173	01/01/2003	01/01/2003 100 kg N 31/12/2003 50 kg N 31/12/2004 50 kg N	30/11/2006 30/11/2010	4	November 30th of 2004, 2006 2007, 2008
6	Osoppo	46°14' N, 13°5' E, 184 m a.s.l.	2003-2010	Poplar	Marte	6173	01/01/2003	01/01/2003 100 kg N 31/12/2003 50 kg N 31/12/2004 50 kg N	30/11/2006 30/11/2010	4	November 30th of 2004, 2006 2007, 2008


Carmagnola (232 m a.s.l.)
Rain
Tmin
Tmax
Temperature (°C)
Rainfall (mm)
Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec
Month


Gemona del Friuli (184 m a.s.l.)
Rain
Tmin
Tmax
Temperature (°C)
Rainfall (mm)
Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec
Month


Δ=ΣRainfall-ΣET0 (mm)
Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec
Month

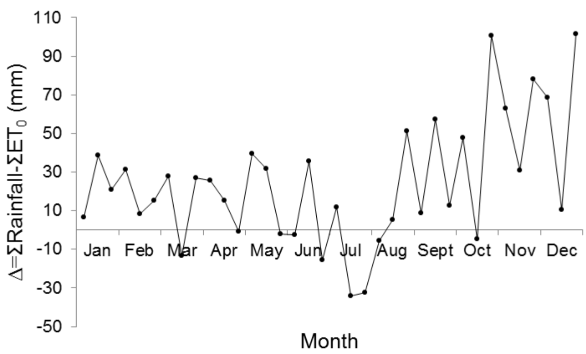

Δ=ΣRainfall-ΣET0 (mm)
Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec
Month

Fig. 4. Monthly mean total rainfall (*Rain*), minimum (*Tmin*) and maximum air temperatures (*Tmax*) for the meteorological series of Carmagnola (2004-2013) and Gemona del Friuli (2003-2010) (on the top). Mean Δ (cumulated rainfall–cumulated reference evapotranspiration) at 10-day intervals (on the bottom).

The material for the analysis comprised three clones of poplar and one clone of willow, which were established between January 2003 and March 2004: *Populus x canadensis* Mönch clone Orion, *Populus x canadensis* Mönch clone I-214, *Populus alba* L. clone Marte and a hybrid of *Salix matsudana* Koidz. clone Levante.

In Lombriasco, clones (Orion, I-214 and Levante) were tested in a randomised complete block design with three replicates. Plants were grown for 10 years in plots of 174 m^2, with a density of 5.747 cuttings ha^{-1}, planted with spacing of 2.9 m x 0.60 m. Neither fertilisation nor irrigation water were applied. Weed control in the first year was carried out with a Pendimethalin treatment (5 kg ha^{-1}) after planting and four mechanical interventions. These latter ones went on also in the second and in the third year (3 and 2 treatments respectively). A chemical weeding was performed in the third year of plantation life with Pendimethalin + Metholaclor (4 kg ha^{-1} + 1 kg ha^{-1}). Insecticide treatments against *Chrysomela populi* L. were necessary during the first (2) and the second year (1). Cutting events were scheduled at the end of the 3rd, 5th, 8th and 10th growing season. To refer to this kind of management it will be hereinafter used the acronym *LomM*.

In Osoppo clone trials (Orion, I-214, Marte) were laid out in a randomised complete block design with four replicates. Plots had a size of 4.100 m^2, a density of 6.173 cuttings ha^{-1} placed 0.6 m apart and with 2.7 m between adjacent rows. SRC plantations were carried on for 8 years. Plots were fertilized with 100 kg N ha^{-1} (NPK 20:10:10) at the stand establishment and with a top dressing of 50 kg N ha^{-1} (NPK 20:10:10) both in 2003 and 2004. Irrigation was not used, because of the abundant rainfall regime characterizing the agro-ecological zone (Fig. 4).

Weeds were controlled chemically during first months after planting with the general herbicide Pendimethalin (5 kg ha^{-1}). In 2003 and 2004 Dicamba herbicide (3,6-

dichloro-2-methoxybenzoic acid) was applied (1.5 kg ha^{-1}) during the vegetative season. I-214 clone was harvested in 2004, 2006 and 2008, Orion and Levante in 2006 and 2008. In short, in Osoppo two kinds of management can be distinguished; the first one, used for I-214 clone, involves three harvests, and it will be re-called using the acronym *Os1M* in the text, whereas in the second type, Orion and Levante like, only two cutting events are scheduled (*Os2M*).

Stands in Lombriasco (Experiment No.1, 2, 3) were established on a sandy loam soil (*LomS*). Replicates of blocks 1 and 2 took place in fields formerly cultivated with continuous corn using high nitrogen fertilisation level, while plants of block 3 grew on a previously fallow area.

Experiments 4, 5 and 6 were conducted on a silt loam soil in Osoppo after continuous corn cropping (*OsS*). Soil texture analyses were carried out before plantation establishment while soil hydrological properties have been obtained using pedotransfer function of Saxton and Rawls (2006).

Table 4. Characteristics of the soils at SRC stand establishment. Soil hydrological properties have been estimated using pedotransfer function of Saxton and Rawls (2006).

Soil Code	Exp. No.	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	Wilting Point (mm mm^{-1})	Field capacity (mm mm^{-1})	Maximum water capacity (mm mm^{-1})	Infiltration rate (mm h^{-1})	Maximum rootable soil depth (mm)
LomS	1, 2, 3	2	51.5	35.2	13.3	1.15	0.088	0.206	0.416	24.64	1500
OsS	4, 5, 6	12	41	53	6	2.6	0.06	0.22	0.467	37.36	430

The estimation of dry aboveground biomass production has been done performing allometric analysis during the plant dormant season and employing allometric functions. The selection procedure of the representative plants sample of the stand and the methodology of measuring live shoots are described in detail in Facciotto et al.

(2005). Sampling dates are reported in Table 3. The equation adopted for poplar plantations in Lombriasco is (Facciotto et al., 2005):

$$\mathrm{AW} = 0.5560 \cdot \mathrm{D}^{2.1952} \quad (34)$$

where the total shoot dry weight (*AW*, g) is function of the shoot diameter (*D* , mm) at breast height (130 cm from the soil surface).

The equation used for willow stands in Lombriasco is published in Cerrillo et al., 2008:

$$\mathrm{AW} = \mathrm{D}^{2.1077} \quad (35)$$

Site-specific allometric functions have been developed for Osoppo trials following guidelines reported by Facciotto et al., 2005 obtaining the following regression equations and correlations:

$\mathrm{AV} = 1.3365 \cdot \mathrm{D}^{2.2393}$ (till the end of 2008) R^2=0.98 (36)

$\mathrm{AV} = 1.0555 \cdot \mathrm{D}^{2.3099}$ (from 2009 to 2010) R^2=0.97 (37)

where *AV* is the wet shoot volume (cm^3).

4.2. Sensitivity analysis

A preliminary sensitivity analysis for SRC parameters against SRC aboveground biomass has been performed to assess the influence of individual parameters on the variable of interest and to identify best candidate parameters for calibration. It has been carried out calculating for each simulation time step the mono-dimensional local sensitivity index $(\partial Y/Y)/(\partial P/P)$, where Y is a response (output) variable of the model and P is a parameter. ∂P is a small variation of the parameter and ∂Y is the related change of the simulated variable.

Parameters chosen for sensitivity analysis are a sub-set of all model parameters. Some parameters have been excluded because of their very nature from calibration: those considered roughly constant over simulation time (e.g. decomposition rates for *SOM* compartments, energy content per unit of material), management parameters decidable by farmers (e.g. water irrigation volume, nitrogen fertilisation level) and parameters intrinsically uncertain (e.g prices of production factors) that need to be investigated with uncertainty analysis.

The decision of considering by default soil parameters calibrable arises from considering their uncertainty (due to personal, sampling and measurement biases or errors, Roy et al., 2003) greater than data manipulation biases (including guesses). Besides, given that a model is simplified representation of the reality, the very own meaning of physical parameter involves a certain level of empiricism. *A posteriori* parameter calibration, so starting from its measured value, could allow to close the existing gap between model representation and reality.

Sensitivity analysis was based on aboveground biomass values simulated during dormant season since biomass in this period is the result of many biophysical processes and therefore it is influenced by all crop parameters (Confalonieri et al., 2009). Stem biomass at resting period constitutes almost completely the entire aboveground biomass, coincidently with allometric analysis.

Sensitivity analysis has been performed for each of the three soil-climate-management combinations simulated (*LomS×LomC×LomM*, *OsS×OsC×Os1M*, *OsS×OsC×Os2M*) starting from default model parameters and considering an increase of 5%.

4.3. Model parameterisation

The model parameterisation and calibration have been carried out for each experimental trial (see Table 3). Every trial consists of a different combination of SRC clone (3 of poplar and one of willow), soil (*LomS*, *OsS*), climate (*LomC*, *OsC*) and management conditions (*LomM*, *Os1M*, *Os2M*).

Calibration has been done against aboveground biomass, estimated from allometric measurements, adopting an iterative procedure. Every procedural step includes two distinct calibrations: the first one performed per clone, independently from management and environmental conditions, the second one conducted per soil. The latter used first-step resulting clone parameter values as input for calibrating soil parameters: gravel, sand, silt, clay and organic matter content, wilting point, field capacity, maximum water capacity, infiltration rate, maximum rootable soil depth, initial soil N-NO_3^- (kg N ha^{-1}) and N-NH_4^+ content (kg N ha^{-1}). The procedure was iterated until reaching clone parameters value stability and the best possible fitting between measured and simulated data.

Calibration was carried out using the iterative Gauss-Newton linearization method (Beck and Arnold, 1977; Draper and Smith, 1981) implemented in a SEMoLa routine, which minimizes the residual sum of square between observed and simulated values.

The agreement between measured and simulated values was quantified by: the maximum absolute error between observed and simulated data (MaxAE), the relative root mean squared error (RRMSE, eq. 38, minimum and optimum = 0%, maximum +∞), the modelling efficiency (EF, eq. 39, ranges between -∞ and 1, optimum=1, if positive the model is a better predictor than the average of measured values), the coefficient of residual mass (CRM, eq. 40, if positive indicates underestimation) and the coefficient of determination (R^2) of the linear regression equation between observed and predicted values ($S_i=a\cdot M_i+b$).

$$\mathrm{RRMSE} = 100 \times \frac{\sqrt{\frac{\sum_{i=1}^{n}(D_i)^2}{n}}}{\overline{M}} \qquad (38)$$

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{n}(D_i)^2}{\sum_{i=1}^{n}(M_i-\overline{M})^2} \qquad (39)$$

$$\mathrm{CRM} = \frac{\sum_{i=1}^{n} M_i - \sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} M_i} \qquad (40)$$

where S_i and M_i, are respectively the i^{th} simulated and the i^{th} measured values, D_i is their difference, n the number of pairs S_i-M_i, $\overline{S}$ and $\overline{M}$ are the averages of simulated and measured values**.**

5. Results and Discussion

5.1. Sensitivity analysis

SEMoLa sensitivity analysis tool identifies the most influential parameters on poplar and willow growth (Table 5). It has been decided to calibrate just nine of them all concerning plant traits: ageing of plantation (*IniSur*, *CS* and *MaxDecSurRate*), plant phenology (growing degree days for starting vegetation *GDDstart*, leaf senescence *GDDsen* and to complete senescence *GDDend*), the photosynthesis efficiency (*RUE*, g DM MJ^{-1}), the fraction of plant aboveground biomass ($Fshoot_T$) and specific leaf area

(*SLA)*. *Fstem* parameter was excluded from calibration since *$Fshoot_T$* parameter affects model upstream. *Kext* maintained its default value derived from literature (0.5, Cannell et al., 1987).

5.2. Calibration

Calibrated values for parameters identified by sensitivity analysis are shown in Table 6. *SLA* values for willow and poplar are consistent with those published in literature (roughly from 1.5 to 4 for poplar and from 1.5 to 2 for willow in the middle crown section as reported in Mamashita et al., 2011). *RUE* values substantially vary within the range proposed by Kiniry (from 1.3 to 1.9, 1998). Willow clone shows greater values of *SLA* and *RUE*, instead there are no substantially differences, in that sense, among poplar clones. Growing degree days for starting vegetation (*GDDstart*), beginning (*GDDsen*) and completing senescence (*GDDend*) are in line with phenological stages visible in field. *$Fshoot_T$* values are coherent with those proposed by Grogan and Matthews (0.75, 2001), Garten et al., 2011 (*$Fshoot_T$*≅0.71), Swamy et al., 2006 (0.77÷0.90) for poplar and by Stadnyk (2010) for willow (0.66÷0.92). There are no clearly defined ranges for *IniSur*, *MaxDecSurRate* and *CS* in literature because their values are extremely variable among clones.

Model calibration allowed to clearly distinguish two soil parameter sets in Lombriasco (Table 7). The first, *Lom1S*, is associated to the blocks 1 and 2 of the trials held in Lombriasco. The second one, named *Lom2S*, is relative to block 3. *Lom1S* has greater $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ initial contents than *Lom2S*, likely due to the residual effects of the previous highly fertilised continuous corn cropping. Calibration has also highlighted minimal differences in terms of texture between the two soils. *Lom1S* resulted a bit more clay and richer in soil organic matter than *Lom2S*. This is reflected in slightly greater available water content into *Lom1S* compared to *Lom2S*. Model has demonstrated to be able to analyse, clarify and solve problem connected with poor data spatial resolution, which prove model validity more than the fitting of simulated data (Sinclair and Seligman, 2000).

The agreement between observed and simulated aboveground biomass values over time computed after parameter calibration is shown for every experimental trial in

Fig. 5.In Lombriasco there is the tendency to overestimate biomass in the first production cycle.

Experimental trials in Osoppo have been less productive than in Lombriasco in spite of a greater SOM initial content, nitrogen fertilisation events and the scarce need of irrigation water (Fig. 4). Obviously, the management plays an important role, but the key reason of the discrepancy is imputable to the maximum rootable depth in the two locations. Root layer in Osoppo can reach the depth of 43 cm while in Lombriasco 150 cm potentially. This guarantees to the root system of stands in Lombriasco to arrive easier at soil water and nutrient reserves. In addition, the greater water infiltration rate of soil in Osoppo rapidly dissolves water surplus.

As far as phenological development is concerned, *ESRC* simulates the bud break and the vegetation phase starting, on average, at the end of March in Osoppo and in the first decade of April in Lombriasco. The complete leaf senescence is reached at the end of October for poplar and in the first 10 days of November for willow.

Whilst stump survival rate is similar among different clones at plantation time, independently from species, it decreases much more rapidly over time in poplar (Fig. 6). *MaxDecSurRate* parameter shows how willow is less sensitive to the highest cutting frequency than poplar. Considering the same clone, the higher is the cutting frequency, the greater is the decrease of stump survival rate over time. The simulated high stump mortality for Marte clone after just the first cut, also revealed by the values of *MaxDecSurRate* and *CS*, pointed out an explosive disease event in field.

ESRC shows an excellent trueness, in terms of CRM, a satisfying precision (EF, RRMSE) and correlation (R^2) in simulating aboveground biomass (Table 8). This is true for both species, both simulating individually each single trial and also working for clone, considering simultaneously different environments (soil×climate×management combinations)

Table 5. Model sensitivity index with respect to calibrable model parameters. Model sensitivity has been tested for the three soil-climate-management combinations simulated. Sensitivity index has computed for an increase of 5% in parameter value, coincidently with cutting events. Parameters are ordered on the basis of the influence they have on the simulation of aboveground biomass production (expressed in terms of model maximum absolute value of sensitivity, from top to bottom). Model average sensitivity to each parameter has been also reported. Selected parameters for calibration are in bold. Parameters towards which model sensitivity is lower than 0.1 have been omitted.

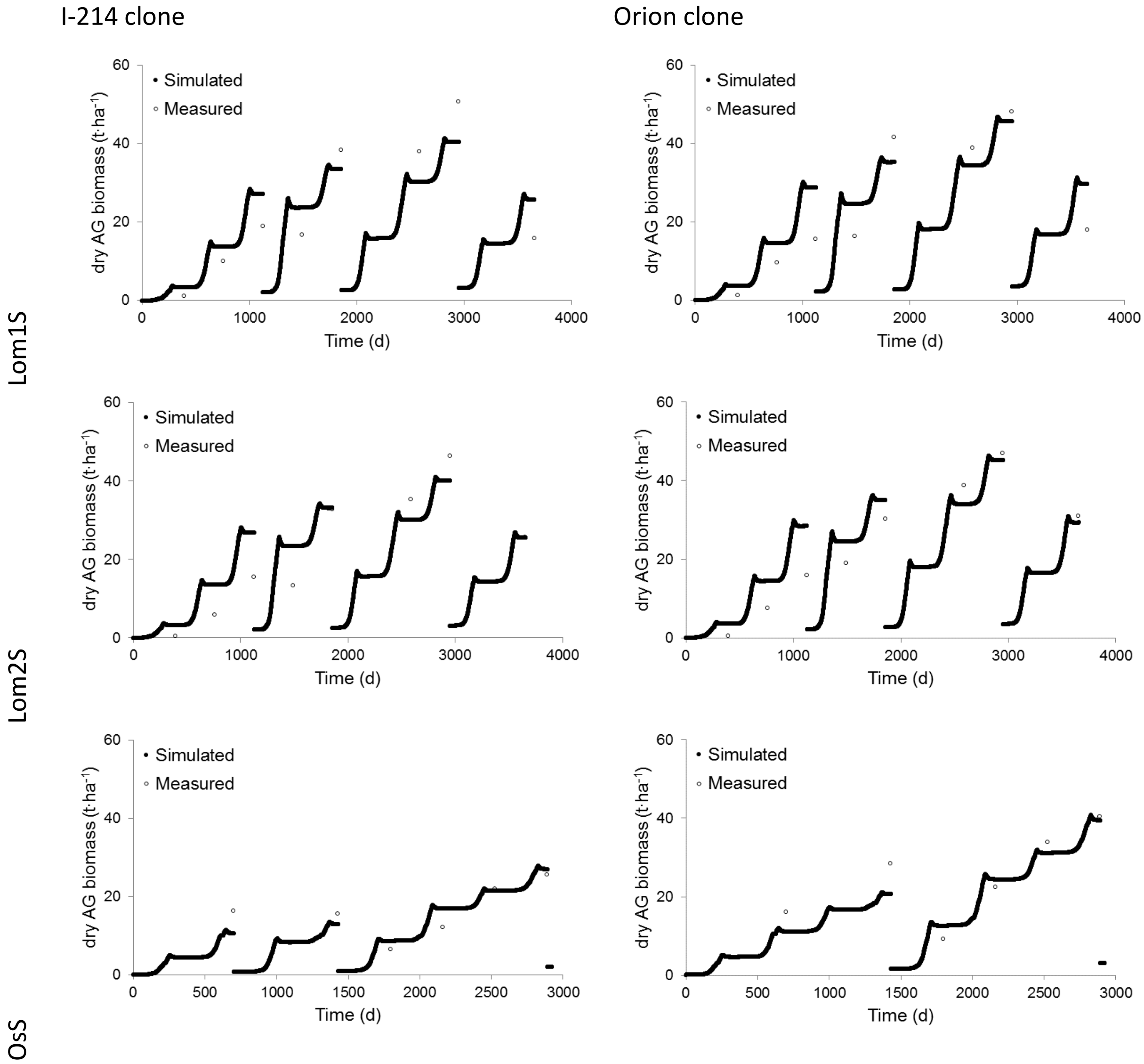
	Model sensitivity at cutting event												
	LomS×LomC×LomM					OsS×OsC×Os1M				OsS×OsC×Os2M			
	Year					Year				Year			
Calibrable parameter	3	5	8	10	mean	2	4	8	mean	4	8	mean	Absolute max
Fstem	-11.24	-10.61	-11.15	-11.57	-11.14	-11.33	-12.14	-12.62	-12.03	-11.78	-12.17	-11.97	12.62
SLA	1.95	1.62	1.70	1.85	1.78	8.55	9.43	9.57	9.18	2.63	2.39	2.51	9.57
GDDsen	3.02	2.62	1.95	2.02	2.41	2.92	5.12	7.28	5.10	3.94	5.26	4.60	7.28
IniSur	2.63	2.59	2.92	3.36	2.88	1.94	2.26	2.56	2.26	3.11	3.21	3.16	3.36
FShootT	2.57	1.12	0.96	0.57	1.31	1.63	0.85	1.06	1.18	3.15	2.04	2.60	3.15
RUE	2.63	2.48	2.48	2.66	2.56	0.68	0.76	0.79	0.74	3.11	3.07	3.09	3.11
Kext	1.95	1.62	1.70	1.85	1.78	2.55	2.82	2.91	2.76	2.63	2.39	2.51	2.91
GDDend	-0.78	-1.82	-2.43	-2.03	-1.76	0.49	-0.98	-2.69	-1.06	-0.29	-2.56	-1.42	2.69
Opt1	-1.54	-1.58	-1.52	-1.46	-1.52	-1.30	-1.76	-1.72	-1.59	-1.56	-1.58	-1.57	1.76
MaxDecSurRate	0.00	-0.11	-0.48	-0.72	-0.33	0.00	0.32	1.18	0.50	0.00	-0.14	-0.07	1.18
GDDStart	-0.28	-0.10	-0.13	-0.11	-0.15	0.43	0.80	1.15	0.79	-0.14	-0.14	-0.14	1.15
Kc2	-1.14	-0.78	-0.65	-0.88	-0.86	-0.60	-0.81	-0.71	-0.71	-0.68	-0.61	-0.64	1.14
GTmin	-0.70	0.16	-1.13	-0.37	-0.51	0.14	-1.05	-0.59	-0.50	-0.45	-0.25	-0.35	1.13
HI	0.00	-0.41	-0.43	-1.03	-0.47	0.00	-0.38	-0.23	-0.20	0.00	-0.19	-0.10	1.03
CS	0.00	0.14	0.34	0.69	0.29	0.00	-0.09	-0.33	-0.14	0.00	0.18	0.09	0.69
Opt2	0.21	0.13	0.27	0.37	0.24	0.45	0.50	0.45	0.47	0.46	0.40	0.43	0.50
C1	0.33	0.14	0.21	0.21	0.22	0.40	0.46	0.48	0.45	0.49	0.44	0.46	0.49
Rmax	0.34	0.08	0.02	0.00	0.11	0.21	0.05	0.03	0.10	0.11	0.03	0.07	0.34
Kdec	-0.12	-0.15	-0.17	-0.13	-0.14	-0.05	-0.20	-0.17	-0.14	-0.12	-0.13	-0.13	0.20
Kc3	0.01	0.03	-0.01	-0.10	-0.01	-0.08	-0.04	-0.04	-0.05	-0.06	-0.09	-0.08	0.10
GTmax	0.03	0.02	0.04	0.06	0.04	0.08	0.09	0.08	0.08	0.08	0.07	0.07	0.09
Kc1	0.03	0.03	0.00	0.00	0.02	-0.07	0.03	0.01	-0.01	0.02	0.00	0.01	0.07
Kc4	-0.01	0.04	0.01	0.00	0.01	0.03	0.03	0.06	0.04	0.02	0.02	0.02	0.06

Table 6. Calibrated sensitive plant parameters.

Clone	SLA	RUE	GDDstart	GDDsen	GDDend	FshootT	IniSur	MaxDecSurRate	CS
I-214	1.8247	1.8358	267	2670	2790	0.769	98.074	9.45	0.3798
Orion	2.0228	1.769	227	2670	2790	0.7511	96.502	7.7091	0.34257
Marte	2.0983	1.783	227	2670	2790	0.78292	94.385	17.711	0.28801
Levante	2.2134	1.9268	227	2720	2840	0.651	96.738	4.8071	0.52671

Table 7. Calibrated uncertain soil characteristics.

Soil Code	Location	Experiment No.	Blocks	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	Wilting point (mm mm^{-}	Field capacity (mm	Maximum water capacity	Infiltration rate (mm h^{-1})	Maximum rootable soil depth	Soil N-NO_3^- content	Soil N-NH_4^+ content (kg N ha^{-1})	Preceding crop
Lom1	Lombriasco	1, 2, 3	1, 2	2	52.2	34.5	12.8	1.18	0.088	0.206	0.416	24.92	1500	22	32	Continuos corn
Lom2	Lombriasco	1, 2, 3	3	2	53.2	35	12.3	1.08	0.081	0.197	0.413	27.2	1500	17	27	Fallow area
OsS	Osoppo	4, 5, 6	1-4	12	41	53	6	2.6	0.06	0.22	0.467	37.36	430	27	37	Continuos corn


I-214 clone
Orion clone
Lom1S
Lom2S
OsS
Simulated
Measured
dry AG biomass (t·ha-1)
Time (d)
0
20
40
60
0
1000
2000
3000
4000
500
1500
2500

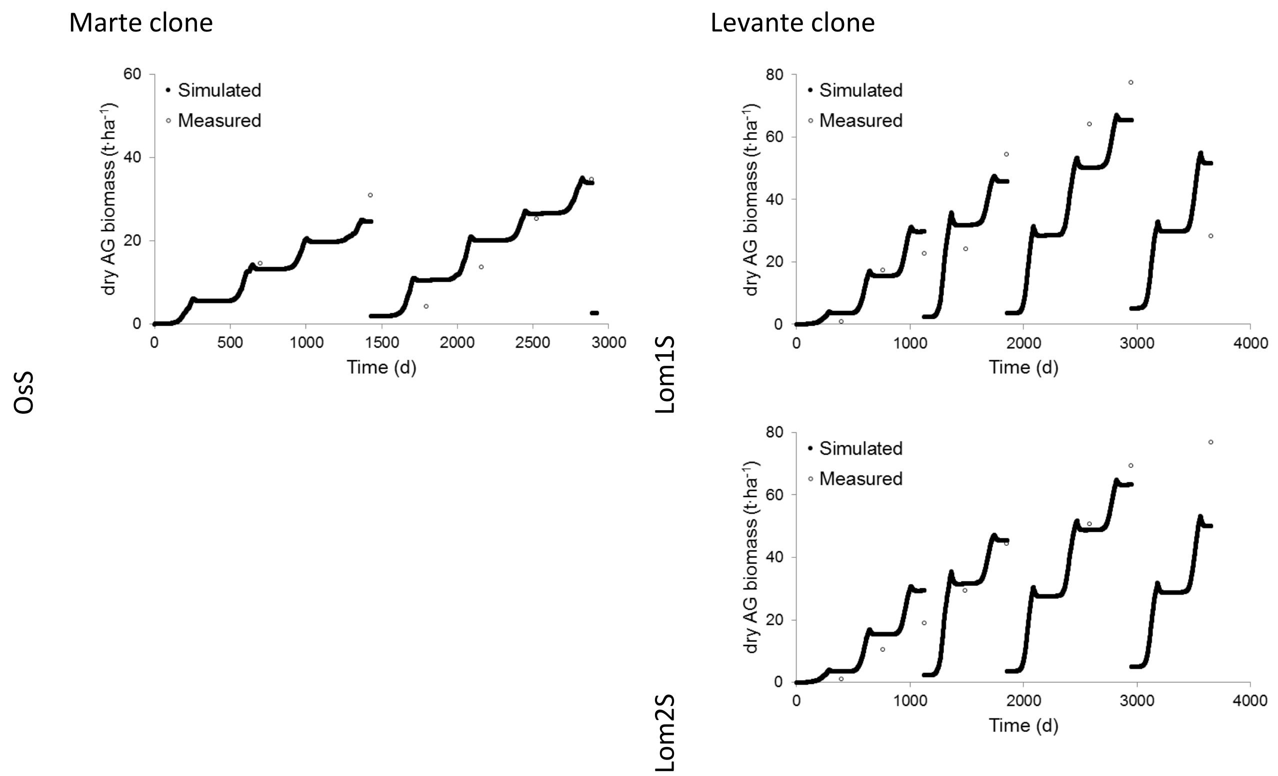


Fig. 5. Simulated and measured dry aboveground (AG) biomass for every experimental trial.

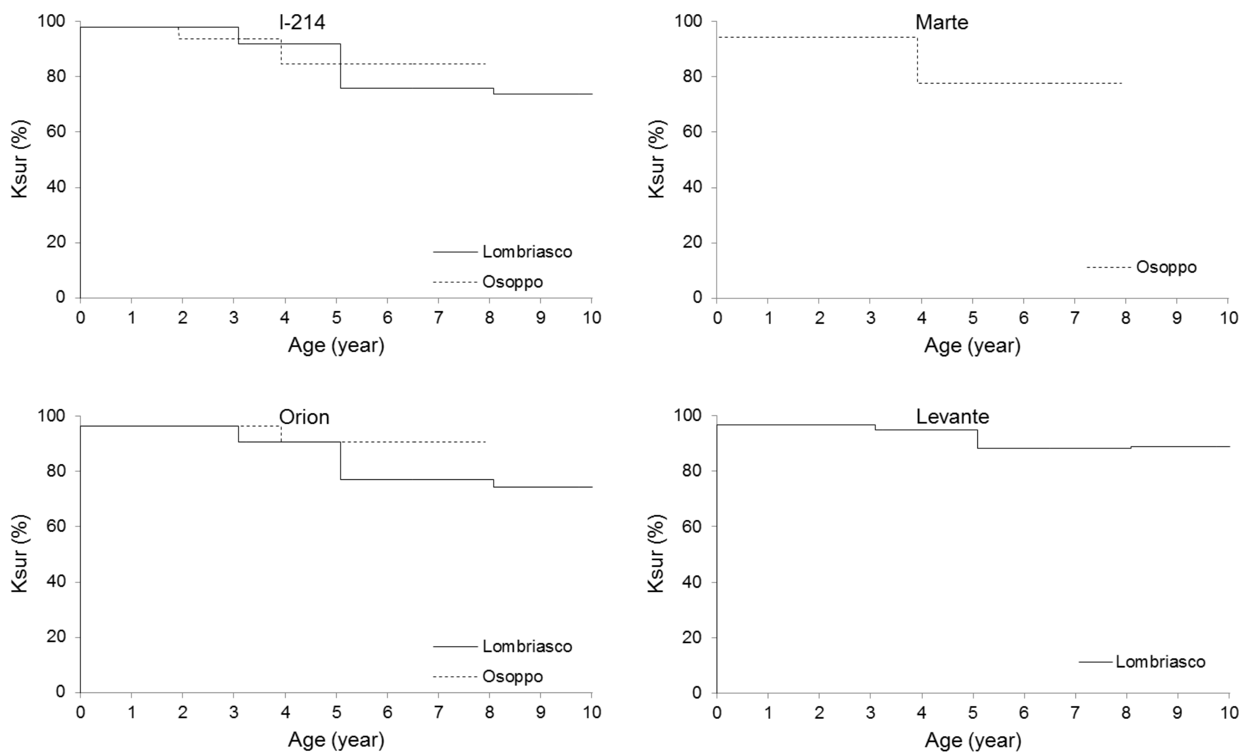


Fig. 6. Dynamics of the simulated stump survival rate over time for the four clones in Lombriasco and

Osoppo. *Ksur* runtime calculation, being dependent only on plantation age (*Age*) and cutting frequency, is independent from soil parameters.

Table 8. Indices of agreement between simulated and measured data.

Clone	Experiment No.	Soil	Climate	Management	n	R^2	EF	CRM ($t\ B^{-1}\ ha^{-1}$)	MaxAE ($t\ B\ ha^{-1}$)	RRMSE	n	R^2	EF	CRM ($t\ B^{-1}\ ha^{-1}$)	MaxAE ($t\ B\ ha^{-1}$)	RRMSE
	1	Lom1S	LomC	LomM	8	0.84	0.79	-0.04	10.25	30.72						
I-214	1	Lom2S	LomC	LomM	8	0.86	0.79	-0.12	11.34	30.83	22	0.82	0.79	-0.06	11.34	26.12
	4	OsS	OsC	Os1M	6	0.73	0.70	0.01	5.80	20.88						
	2	Lom1S	LomC	LomM	8	0.83	0.76	-0.15	13.08	32.56						
Orion	2	Lom2S	LomC	LomM	8	0.89	0.83	-0.13	12.49	25.46	22	0.83	0.80	-0.08	13.08	29.69
	5	OsS	OsC	Os2M	6	0.87	0.84	0.07	7.75	16.92						
Marte	6	OsS	OsC	Os2M	-	-	-	-	-	-	6	0.86	0.82	-0.04	6.37	22.17
Levante	3	Lom1S	LomC	LomM	8	0.79	0.78	-0.02	23.27	32.00	16	0.83	0.80	0.02	26.83	30.15
	3	Lom2S	LomC	LomM	8	0.88	0.83	0.05	26.83	28.32						

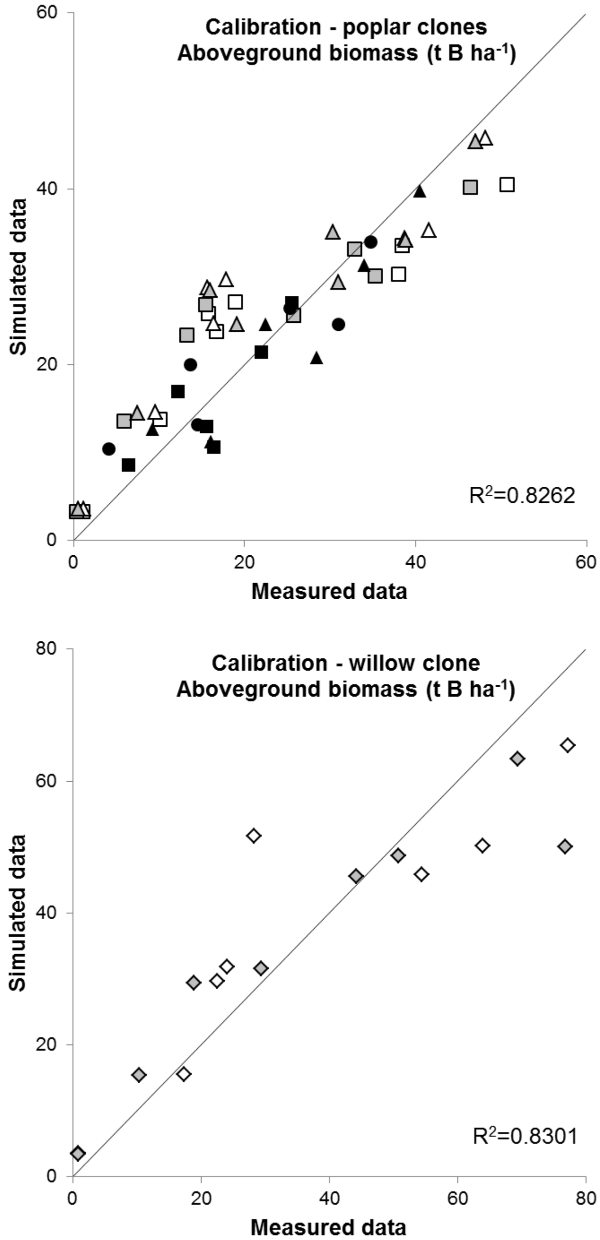


Fig. 7. Simulated vs. measured aboveground biomass data at dormant season. On the left results for the three poplar clones: I-214 (marked with squares), Orion (triangles) and Marte (circles). On the right results for Levante willow clone (diamonds). Markers are also distinguished for soil: *Lom1S* in grey, *Lom2S* in white and *OsS* in black.

6. Conclusions

There is the need to consider factors often neglected in *ex ante* SRC impact assessment studies like (i) the interactions of species/genotype with management conditions, soil and climate environments, (ii) the need to consider at the same time the economic, environmental and agronomic consequences of adoption, and (iii) the importance of modelling the performances of innovations at the farm level, in particular for innovative crops. Compared to on-farm trials, *ESRC* has proved to be reliable on simulating aboveground biomass production of different poplar and willow clones, grown on different soils, under various management and climate conditions. *ESRC* makes SRC impact assessment possible quickly and with few resources provided it is applicable in regional situations where the farms and crops are well characterized.

The adopted user-oriented modelling approach allows to easily run and parameterise the model and to set simulation. Being implemented in SEMola language, model is customizable with ease, also from non-programmer users. The modularity structure makes simple model development, implementing and linking modules, specific for other domains, to the main architecture.

ESRC could be an useful tool i) used as decisional system for optimising cutting cycles length in order to reach the best productive results; ii) for investigating through scenario analysis the effect of climate uncertainty on biomass production; iii) to support studies on how ligno-cellulosic species can contribute to mitigation of greenhouse gases emission and more in general, to facilitate the formulation of strategic orientations for agronomic innovation research.

Further improvements of *ESRC* should focus on the enhancement of its descriptive power for key processes, as well as on parameterisation, re-calibration and validation using spatio-temporal datasets across a wider domain so that it can be more applicable to broader regions.

Acknowledgments

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5. Conclusions

This doctoral work has the purpose of contributing in the field of research of "ammonia emissions from animal slurry" in SRC, with experimental "on field" work and a new mechanistic model that has been developed to simulate the growth of poplar and willow under short rotation coppice. This topic has been collecting great interest, since in the 80's the nitrogen bomb was recognized as a global issue, a concern for human health and environmental quality, and the energetic crisis of 70's has led to a new conscience on energetic themes, that are strictly related with sustainability, defined as the intersection of the social, economic and environmental spheres. International Protocols have focused strategies to face the nitrogen challenge, and in the European scenario characterized by some countries with intensive animal husbandry, those measures have been implemented effectively. A great work has been done by the European scientific community that with the BAT (Best Available Techniques) has put great attention on animal husbandry and mitigation strategies to reduce the load of nitrogen on agricultural land and water bodies, as well ammonia emission, that is a well-known problem for European agriculture. The common line of this doctoral study stays in the manure management chain, that starts with the collection of manure in animal houses, continues with the storage in order to mature slurry, and ends with its spreading on field. For all these phases, there are opportunities to reach a better sustainability for European agriculture. Apart from the animal houses, not the core of this thesis, I had the great opportunity to contribute in a research group with a multidisciplinary approach and study many aspect of the issue, that are to taken together to give a response on the complexity of the issue. Still there is a global uncertainty in the assessment of ammonia emission. Storage of slurry are required to respect regulations and in this phase, without applying some measure, high losses in emission can occur, giving fertilizer not valuable and a damage for the environment. Even within countries, due to structural differences in agricultural, there may exist substantial differences in emission factors among regions. For the storages there is a great influence of temperature on the emission process, that is the most relevant environmental parameter, followed by pH and wind speed. The comparison between Denmark and Italy has evidenced a great difference in ammonia emission, in the warmer Italy almost 80% more than Denmark. This is confirmed by some operative studies, but in our case, with the development of a mechanistic model, we have found scientific relationships that explain the pattern in ammonia emission from the storage stage, that can be very variable. Some measures should be implemented: avoiding lagoon as a slurry storage, and the construction of higher tank, because of the reduced surface exposed to the atmosphere. The second is the coverage of slurry, that is a cost but can give great results, as confirmed by many studies in literature. The third is the acidification of slurry, as a consequence of the great role of pH in ammonia emission. The best solution seems to be the permanent cover of slurry, that can be done with some materials tested in a number of studies found in literature. The spreading of slurry is a phase that presents great possibilities to reduce nitrogen pollution: spreading techniques have a crucial role, but also the choice of the distribution period in function of meteorological conditions have a great impact on ammonia emission. Measuring ammonia, an important part of this work, is a recognized difficult task. It is a sticky compound that is subjected to chemical reactions in atmosphere, and still there is a lack of a standard methodology, but a number of techniques can be used depending on the experimental conditions and, of course, the researcher's financial resources. As a preliminary research, in the first year of doctorate we have developed a methodology. Chambers method has been identified as the best option for the experimental conditions of our studies, because of the small size of plots and the neighborhood of comparative thesis, and the availability of a high precision photo-acoustic monitor has driven our research unit to this direction. Among meteorological variables, it is clear that temperature has a major impact respect to wind speed. In slurry distribution, as confirmed by field experience, the most important thing is the techniques engaged. There are on the market a number of options, but the most environmental friendly also have high costs. Despite the spreading technique, short rotation coppice crops can be considered a way to recycle waste and slurry, limiting the nitrogen losses that are a consequence of the intensive farming systems adopted at European scale. In our research projects we have seen that the best results come from the injection of slurry, with values of ammonia emission that are approximately zero. However, these technique reveals problems because of the nitrogen that are available to be lost in the groundwater, and the stimulation of methane emissions. There are some measures that have a better impact on the environment respect to the traditional and less expensive wide spreading, but that do not have its criticalities (trailing hose, trailing shoes). In conclusion, it is suggested that an interesting option could be a financial aid for the farmers that adopt these techniques and perform spreading events in occasion of favorable meteorological conditions. According to European Union, that recently has modified the list of BAT (Best Available Techniques), recognizing the critical issues addressed by injection. Bioenergy crops are a promising option for integrating fossil fuels and achieving European environmental targets. Among these, Short Rotation Coppice and crops are considered an opportunity for sustainable agricultural development. Two publications have been followed by me, and the scientific output that I get from these works is that short rotation coppice should be better studies in order to perform a modelling approach, and that the initial stage of short rotation coppice is a critical phase in which fertilization is suggested to be partitioned in small amounts and put localized and with the right meteorological conditions, in order to reduce ammonia emission and nitrate leaching respect to traditional crops. However, the specificity of tree plantation is a good practice to reduce nitrogen pollution in the following years, when the short rotation coppice can be considered a mature system. An innovative feature of this thesis was the modelling of short rotation coppice, in order to prove that it can be an interesting strategy to limit nitrogen pollution and contributing to sustainability in agriculture. In fact this area of research still needs attention, because without the regional characterization of genotypic characteristics of crops (willow and poplar for our purposes) it is very difficult forecast the important investments by farmers that are required to develop the biomass chain. There is the need to consider factors often neglected in *ex ante* SRC impact assessment studies like the interactions of species/genotype with management conditions, soil and climate environments, the need to consider at the same time the economic, environmental and agronomic consequences of adoption, and the importance of modelling the performances of innovations at the farm level, in particular for innovative crops. Using the ESRC model we have found that there is a good agreement between simulated versus measured values, and that there are good statistical evidences that poplar and willows have good yield potential in the North of Italy. However, the model must be validated using a wide number of data. The Validation of a model like ESRC is a time consuming activity that is still in progress. Climate changes are also an interesting question that has a strong influence on Short Rotation Coppice yields. A future outlook in the field of research will perform more scenario analysis, to investigate the response of crops related with these changes. For the same reason in other researches, further development of this argument will be the study of the GHG emissions from short rotation coppice, a complete economic evaluation of sustainability, and the validation of models under different scenarios.

As a final conclusion, it can be said that SRC can be an efficient way to recycle slurry and to limit ammonia emissions, but the importance of structural political planning still remain necessary to sustain economically these crops. Financial aid and the organization at a local scale of short rotation coppice crops should be done in order to make these crops a real opportunity for farmers.

In the end, it is my opinion that chemical fertilizers should be more considered for their potential pollution, in order to favor the agricultural use of organic fertilizers, especially animal slurries.

6. Publications

In this thesis are presented the following works that have been sent to peer review journal.

Candoni F. da Borso F. Danuso F. (2015) A model to assess ammonia emission from liquid manure storage with applications to Denmark and Italy. Sent to Italian Journal of Agrometerology.

Ginaldi F., Candoni F., Bergante S., Facciotto G., Borek R., Danuso F. (2016) ESRC model for short rotation woody coppice. Sent to Biomass and Bioenergy

Gumiero B., Candoni F., Boz B., da Borso F., Colombani N., Mastrocicco M. (2016) Organic fertilization and N dynamics during the initial stage of *Platanus hispanica* in short rotation forestry. Sent to Agriculture Ecosytem&Environment

Candoni F., Da Borso F., Boz B., Gumiero B. (2016) Organic fertilization and N dynamics during the mature stage of *Platanus hispanica* in short rotation forestry Prepared for technical report of Veneto Agricoltura

Poster presentation at international/national congress

Candoni F., da Borso F., Danuso F., Ginaldi F., Sommer S.G. (2014) Assessing ammonia emissions from liquid manure storage: a modelling approach applied to Danish and Italian Conditions. Proceeding for the 18th Nitrogen Workshop, Lisbon, Portugal,30th June - 5th July 2014

Candoni F., Danuso F., Baldini M., Ginaldi F. (2014) The suitability of Giant reed and Miscanthus silages for biogas production: a preliminary comparison, XLIII° Convegno della Società Italiana di Agronomia, Pisa 17-19 September 2014

Ginaldi F., Delle Vedove G., Candoni F., Ferfuia C., Pošćić F., Alberti G., Peressotti A., Danuso F. (2015) CSS-CropEnviron: a module of CSS (Cropping System Simulator model) for the GHGs dynamic balance of crops. 50th Croatian & 10th International Symposium on Agriculture, Opatija, February, 16-20

Da Borso F., Chiumenti A., Candoni F., Limina S. (2013) Multifunzionalità delle Afi in zone agricole di alta pianura. Convegno RURALIA, Multifunzionalità del paesaggio nelle aree rurali, Udine 25 Ottobre 2013

Acknowledgments

I wish to thank Francesco da Borso and Francesco Danuso for their kind collaboration, and Fabrizio Ginaldi for many useful advises.