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PHD DISSERTATION

# APPROACHES FOR AGRO-ENERGY LAND PLANNING

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## Dedication

This thesis is especially dedicated to my grandmother Onda who brought me up.

It is also dedicated to Natascia and Franco that now are my family.

## Acknowledgements

Thanks to Francesco who is an example in the life and work.

Thanks to Alvaro, Oxana, Elena and Marco with whom I have lived many adventures.

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Thanks to Marta who made me a better guy.

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# 1

# General introduction

Fabrizio Ginaldi

## 1.1. Preface

The past half-century has been marked by growth in food production, allowing for a dramatic decrease in the proportion of the world's people that are hungry, despite a doubling of the total population (World Bank, 2008; FAOSTAT, 2009). Nevertheless, more than one out of seven people today still do not have access to sufficient protein and energy from their diet, and even more suffer from some form of micronutrient malnourishment (FAO, 2009). The world is now facing a set of intersecting challenges (Evans, 2009). The global population will continue to grow, yet it is likely to plateau at some 9 billion people by roughly the middle of this century (Godfray *et al*., 2010). A major correlate of this deceleration in population growth is increased wealth, and with higher purchasing power comes higher consumption and a greater demand for processed food, meat, dairy, and fish, all of which add pressure to the food supply system. At the same time, food producers are experiencing greater competition for land, water and energy; and it is becoming increasingly clear the need to curb the many negative effects of food production on environment (Tilman *et al*., 2001; Millenium Ecosystem Assessment, 2005).

The increase of population and welfare will increase energy demand. The expected shortage of main energy sources, in the long term, solicit new energy strategies to fill the increasing demand supply gap (European Commission, 2009). Besides the issue of depletion, fossil fuel use presents serious environmental problems, particularly global warming. Also, their production costs will increase as reserves approach exhaustion and as consequence of more expensive technologies used to explore and extract less attractive resources. Finally, oil supply security causes concerns: mainly because of the politically unstable regions of the world oil comes from (Goldemberg, 2007). Shifting society's dependence away from petroleum to renewable biomass resources is generally viewed as an important contributor to the development of a sustainable industrial society and effective management of greenhouse gas emissions. Biomass represents an abundant potential carbon-neutral renewable resource for the production of bioenergy and biomaterials, and its enhanced use would address to several societal needs (Ragauskas *et al*., 2006). The current European legislation (European Commission, 2009) has imposed as mandatory national targets for 2020 the use of energy from renewable sources (for Italy 17 % of gross final energy consumption should be accounted for renewable sources energy).

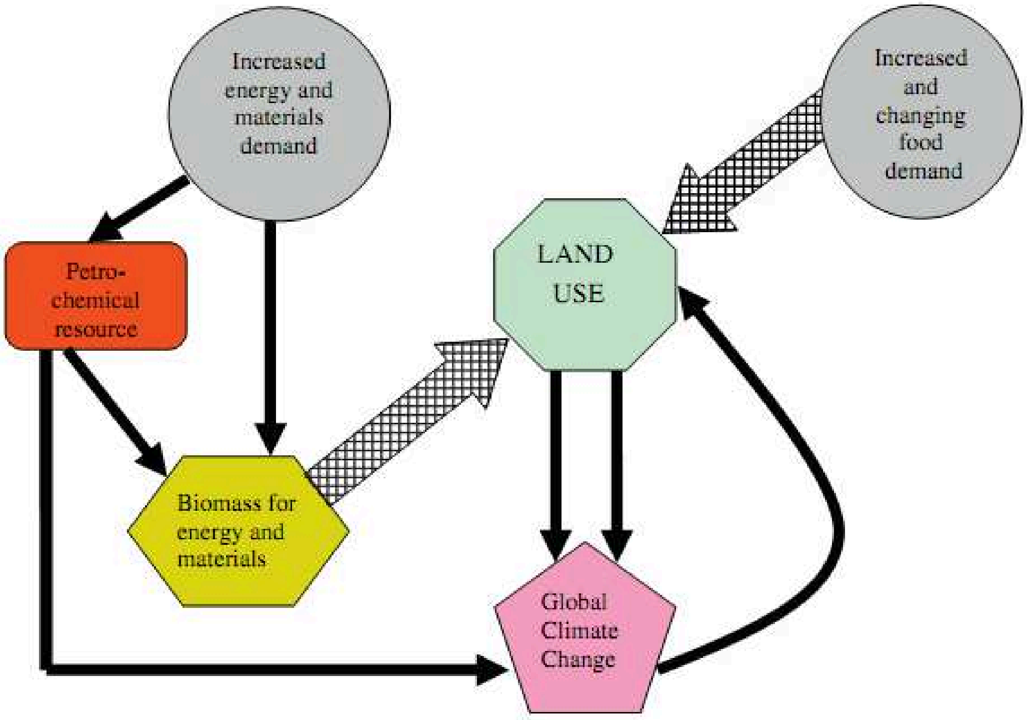


Fig. 1.1. Trilemma challenge (Source: Harvey and Pilgrom, 2011).

When increased demand for food and energy combine, pressure on land conversion increases, leading to further climate change: as a result it may affect productivity and availability of land, and creating a potential vicious circle. That is the trilemma challenge (Fig. 1.1, Tilman *et al*., 2009).

## 1.2. Trilemma challenge

This paragraph aims to analyse the trilemma challenge and briefly discuss the interactions among its components.

The increased competition for use of land derives from the rise in world population (from 6.5 billion to 9 billion by 2050), the changing demand for food, and the goal to reduce the scale of malnutrition (IAASTD, 2009; Evans, 2009; Royal Society, 2009; Pretty, 2008). Since mid-1980s productivity growth has fallen below the rate of population growth. Without productivity growth commensurate with demand growth, pressures to increase the amount of land under cultivation for food production will increase.

Concurrently energy demand increase and rapid oil stocks depletion (Aleklett *et al*., 2010) could lead to an emerging energy gap of roughly 15 % between supply and demand

(IEA, 2008; 2009) within the next two decades. As a consequence turbulence in oil prices will provoke successive waves of stuttering growth followed by severe depression (Hirsch *et al*., 2005; Cavallo, 2005; Sorrel *et al*., 2009; Lloyds, 2010). The relationship between the price of oil barrel and Gross Domestic Product (GDP) growth is well-established, with high prices and oil shocks contributing significantly to historical recessions (Jones *et al*., 2004; Bird, 2004). Less developed, oil dependent regions are particularly vulnerable (Birol, 2008). One of the key negative feedbacks of high oil prices concerns the reduction in agricultural productivity. High oil prices raise agricultural inputs (pesticides and nitrogen fertilizers), transport, tillage and irrigation systems costs; this is likely to produce declines in agricultural productivity, so exacerbating the pressures to expand cultivated land area at lower levels of productivity (Murray, 2005; Overseas Development Institute, 2008; Burney *et al*., 2010). On the other hand diminishing fossil fuel energy supplies, in particular for transport, demand for alternative sources of liquid transport fuels is likely to increase.

Biofuels are likely to be promoted as a substitute for oil both for objectives of energy security, economy, and sustainability (Pacala and Socolow, 2004; Farrell *et al*., 2006). First generation biofuels are made from sugars and vegetable oils found in arable crops and comprises biodiesel (bio-esters), ethanol and biogas for which the production process is considered 'established technology'. Biodiesel is a substitute of diesel and is produced through transesterification of vegetable oils (from sunflower, rapeseed, soybean, palm, jatropha), and residual oils and fats, with minor engine modifications. Bioethanol is a substitute of gasoline and it is a full substitute for gasoline in so-called flexi-fuel vehicles. It is derived from sugar or starch (grain, sugar cane, potatoes, corn) through fermentation. Bioethanol can also serve as feedstock for ethyl tertiary butyl ether (ETBE) which blends more easily with gasoline. Biogas, or biomethane, is a fuel that can be used in gasoline vehicles with slight adaptations. It can be produced through anaerobic digestion of liquid manure and other digestible feedstock. At present, biodiesel, bioethanol and biogas are produced from commodities that are also used for food. Second generation biofuels arise from lignocellulosic material that makes up the majority of cheap and abundant no food materials available from plants (agricultural and forest wastes, short rotation forestry crops - poplar, willow, eucalyptus -, perennial grasses - miscanthus, switch grass, reed canary grass -) (Naik *et al*., 2010). But, at present, production of such fuels is not cost effective because of a number of technical barriers that need to be overcome to carry out fully their potential (Eisberg, 2006). However, demand scenario for biofuels is significantly determined by a combination of different political objectives and oil price. The prospect of scaling up biofuel production has raised a variety of concerns including conflicts in respect to food supplies, water resources, biodiversity, and even additional greenhouse gas (GHG) emissions.

Sometimes energy crops compete with food crops for land and this represents a big mistake, because only lands abandoned from agricultural use should be dedicated to energy purpose (Tilman *et al.*, 2009). Furthermore, rapid expansion of global biofuel production (from grain, sugar, oilseed crops) and sudden rise in the petroleum price have caused valuation convergence between petroleum and agricultural commodities; prices for crops that can be used for both food and fuel are now determined by their value as biofuel feedstock rather than human food or livestock feed (Cassman and Liska, 2007).

Environmental impacts of agriculture, both for food and energy purposes, include those caused by expansion (when croplands and pastures extend into new areas, replacing natural ecosystems) and those caused by intensification (when existing lands are managed to be more productive, often through the use of irrigation, fertilizers, biocides and mechanization). Agricultural expansion has had tremendous impacts on habitats, biodiversity, carbon storage and soil conditions. In fact, worldwide agriculture has already cleared or converted 70 % of the grassland, 50 % of the savannah, 45 % of the temperate deciduous forest, and 27 % of the tropical forest biome (Ramankutty and Foley, 1999; Ramankutty *et al.*, 2008). Agricultural intensification has dramatically increased in recent decades, outstripping rates of agricultural expansion, and has been responsible for most of the yield increases of the past few decades. In the past 50 years, the world’s irrigated cropland area roughly doubled, while global fertilizer use increased by 500 % (over 800 % for nitrogen alone). Intensification has also caused water degradation, increased energy use and widespread pollution (Foley *et al.*, 2011). Fertilizer use, manure application and leguminous crops (which fix nitrogen in the soil) have dramatically disrupted global nitrogen and phosphorus cycles (Vitousek *et al.*, 1997; Smil, 2000; Bennett *et al.*, 2001), with associated impacts on water quality, aquatic ecosystems and marine fisheries (Diaz and Rosenberg, 2008; Canfield *et al.*, 2010).

Both agricultural expansion and intensification are also major contributors to climate change. Agriculture is responsible for 30–35 % of global greenhouse gas emissions, largely from tropical deforestation, methane emissions from livestock and rice cultivation, and nitrous oxide emissions from fertilized soils (Stern, 2007; Foley *et al.*, 2011). Generally, a change in land use entails a change in soil characteristics and land vegetation. In the present context, relevant characteristic of soil and vegetation is its carbon content, which one may express as kg-carbon per $m^2$ of land. As carbon is exchanged among plants, soils, and the atmosphere, any change in equilibrium carbon content of plants or soils changes carbon content of atmosphere and hence is tantamount to a positive or negative flux of $CO_2$ to the atmosphere. The impact of this positive or negative $CO_2$ flux can, after certain adjustments, be added to other GHG emission impacts from lifecycle of bioenergy to produce a comprehensive measure of bioenergy impact on climate (Delucchi, 2011).

In the debate on land use, the terms “direct land-use change” (dLUC) describe changes connected to a field where biofuel crop cultivation is taking place. However, if the area was previously utilised for other purposes, that activity might be displaced to other areas. The environmental effects of indirect land-use change (iLUC) are known as leakage i.e. the result of an action occurring in a system that induces effects, indirectly, outside the system boundaries but that can be attributed to the action occurring in the system. The displacement of current land-use for biofuels production can generate more intense land-use elsewhere (Turner *et al*., 2007; Di Lucia *et al*., 2012).

Most prior studies have found that substituting biofuels for gasoline will reduce GHGs because biofuels sequester carbon through the growth of the feedstock. These analyses have failed to count the carbon emissions that occur as farmers worldwide respond to higher prices and convert forest and grassland to new cropland to replace the grain (or cropland) diverted to biofuels (Searchinger *et al*., 2008). The loss of maturing forests and grasslands foregoes ongoing carbon sequestration as plants grow each year, and this foregone sequestration is the equivalent of additional emissions. Alternatively, farmers can divert existing crops or croplands into biofuels, which causes similar emissions indirectly. Studies have confirmed that higher soybean prices accelerate clearing of Brazilian rainforest (Morton *et al.*, 2006). Projected corn ethanol in 2016 would use 43 % of the U.S. corn land harvested for grain in 2004 (Searchinger *et al.*, 2008), overwhelmingly for livestock (ICGA, 2013), requiring big land-use changes to replace that grain.

As existing land uses already provide carbon benefits in storage and sequestration (or, in the case of cropland, carbohydrates, proteins, and fats), dedicating land to biofuels can potentially reduce GHGs only if doing so increases the net carbon benefit of land. Technically, to generate greenhouse benefits, the carbon generated on land to displace fossil fuels (the carbon uptake credit) must exceed the carbon storage and sequestration given up directly or indirectly by land uses changing (the emissions from land-use change). Current policy on corn-based ethanol, considering also land use change emission, instead of producing 20 % of GHG savings, nearly doubles greenhouse emissions over 30 years and increases GHGs for 167 years (Searchinger *et al.*, 2008).

## 1.3. Sustainability

The World Commission on Environment and Development (WCED) in 1987 defined "sustainable development" as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987).

Tilman *et al*. (2002) defined sustainable agriculture as practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered. If society is to maximize the net benefits of agriculture, there must be a fuller accounting of both costs and benefits of alternative agricultural practices, and such an accounting must become policy, ethic and action basis. Ecosystems provide food, fibre, fuel and materials for shelter; additionally they provide a range of benefits that are difficult to quantify and have rarely been priced. Intact forests can minimize flooding by slowing snowmelt and water discharge, moderate regional climate, and remove and store atmospheric carbon dioxide, a greenhouse gas. Forest and grassland ecosystems can create or regenerate fertile soils, degrade plant litter and animal wastes, and purify water, and this regenerative process is essential for subsistence slash-and- burn farming systems. The recharge of streams and aquifers by intact ecosystems provides potable water for little more expense than the cost of its extraction.

The intensification of agriculture has broken what was once the tight, local recycling on individual farms nutrients. The green revolution turned crop genetics, inexpensive pesticides and fertilizers, and mechanization developments into greater yields. Further advances, such as precision agriculture (in which fertilizer application rates and timing are adjusted differentially across a field to meet crop needs) will increase agricultural efficiency and decrease adverse effects on the environment (Tilman, 1998; Tilman *et al.*, 2011).

Comparing biofuels with petroleum it must be considered all the effects of alternative choices on the four sustainability pillars: good governance, social development, environmental integrity and economic resilience (Scharlemann and Laurance, 2008).

Studies must consider impacts arising from all the steps that compose production chain biofuel following a life cycles assessment (LCA) approach. LCA is a methodology to assess all environmental impacts associated with a product, process or activity identifying, quantifying and evaluating all the resources consumed, all emissions and wastes released into environment (Brentrup *et al*., 2001).

There are many difficulties in making sustainability operational. Over what spatial scale should food or bioenergy production be sustainable? Clearly an overarching goal is global sustainability, but should this goal also apply at lower levels, such as regions, nations, or farms? Could high levels of consumption or negative externalities in some regions be mitigated by improvements in other areas, or could some unsustainable activities in cropping system be offset by actions in non-cropping sector (through carbon-trading, for example)? Though simple definitions of sustainability are independent of time scale, in practice, how fast should we seek to move from status quo to a sustainable food system? The challenges of climate change and competition for water, fossil fuels, and other resources suggest that a rapid transition is essential. Nevertheless, it is also legitimate to explore the possibility that superior technologies may become available and that future generations may be wealthier and, hence, better able to absorb the costs of the transition. Finally, we do not yet have good enough metrics of sustainability, a major problem when evaluating alternative strategies and negotiating trade-offs. Also a danger is that an overemphasis on what can be measured relatively simply (carbon, for example) may lead to ignore harder quantifying dimensions (such as biodiversity) (Godfray *et al*., 2010).

The provision of sustainably grown agricultural products faces a strong trade-off with the provision of bioenergy, if both are to contribute significantly on a global scale. The reason is the potential incompatibility of burning significant amounts of biomass for bioenergy production with alternative more sustainable forms of agriculture that rely on biomass inputs (e.g. organic farming) instead of inorganic fertilisers for their nutrient balance (Muller, 2009).

The search for beneficial biofuels should focus on sustainable biomass feedstocks that neither compete with food crops nor directly or indirectly cause land-clearing and that offer advantages in reducing greenhouse-gas emissions. Perennials grown on degraded formerly agricultural land, municipal and industrial sold waste, crop and forestry residues,

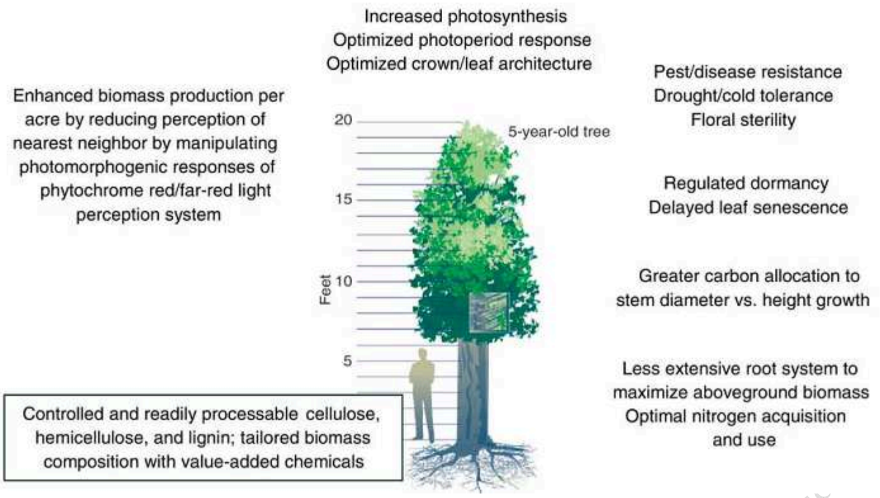


Fig. 1.2. Overview of plants traits that can be targeted by accelerated domestication for enhanced biomass production and processing (Source: Ragauskas *et al*., 2006).

and double or mixed crops offer great potential. They represent the best biofuel sources to be used as substitutes for fossil energy (Tilman *et al*., 2009).

The grand challenge for biomass production is to develop crops with a suite of desirable physical and chemical traits while increasing biomass yields by a factor of 2 or more. Although many annual crops benefit from centuries of domestication efforts, perennial species that could play a central role in providing a renewable source of feedstock for conversion to fuels and materials have not had such attention to date. Doubling the global productivity of energy crops will depend on identifying the fundamental constraints on productivity and addressing them with modern genomic tools (Fig. 1.2, Ragauskas *et al*., 2006).

## 1.4. Tools for sustainability assessment

Ness *et al*. (2007) defined sustainability assessment as a tool to provide decision-makers with an evaluation from global to local integrated nature-society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable. The paper classifies assessment tools according to the following factors:

i) Temporal characteristics, i.e. if the tool evaluates past development (ex-post or descriptive), or if it is used for predicting future outcomes (ex-ante or change-oriented) such as a policy change or an improvement in a production process;

ii) The focus (coverage areas), for example, if their focus is at the product level, or on a proposed change in policy;

iii) Integration of nature-society systems i.e. to what extent the tool fuses environmental, social and/or economic aspects.

The resulted framework consists of three umbrellas or general categorisation areas (Fig. 1.3):

1) Indicators and indices, which are further broken down into non-integrated and integrated. An indicator is a quantitative or a qualitative measure derived from a series of observed facts that can reveal relative positions (e.g. of a country) in a given area. When evaluated at regular intervals, an indicator can point out the direction of change across different units and through time. When indicators are aggregated in some manner, the resulting measure is an index. The index should ideally measure a multi-dimensional concepts which cannot be captured by a single indicator, e.g. competitiveness, industrialisation, sustainability, single market integration, knowledge-based society (Nardo *et al*., 2005);

2) product-related assessment tools with focus on the material and/or energy flows of a product or service from a life cycle perspective. They allow both retrospective and prospective assessment that support decision making. The most established and well-developed tool in this category is Life Cycle Assessment (LCA);

3) Integrated Assessment (IA) has been defined as ‘‘an interdisciplinary and participatory process combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena’’ (Rotmans and van Asselt, 1996). In the context of sustainability assessment, integrated assessment tools have an *ex-ante* focus and often are carried out in the form of scenarios to compare new policy and technology impacts. Many of these integrated assessment tools are based on systems analysis approaches and integrate nature and society aspects. Integrated assessment consists of wide-array of tools for managing complex issues (Gough *et al*., 1998). This wide-array includes the development of conceptual models and software for system dynamics simulation, the Multi-Criteria Analysis, Risk Analysis, Uncertainty Analysis and Cost Benefit Analysis.

A model is “a simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system” (US EPA, 2009). Computational models use measurable variables, numerical inputs, and mathematical relationships to produce quantitative outputs. A model developer sets boundary conditions and determines which aspects of the system are to be modeled, which processes are important, how these processes may be represented mathematically, and what computational methods to use in implementing the mathematics. Thus, models are based on simplifying assumptions and cannot completely replicate the complexity inherent in environmental systems. Despite these limitations, models are essential for a variety of purposes in the environmental field. These purposes tend to fall into two categories:

- To diagnose (i.e., assess what happened) and examine causes and precursor conditions (i.e., why it happened) of events that have taken place;
- To forecast outcomes and future events (i.e., what will happen).

Models can be classified in various ways - for example, based on their conceptual basis and mathematical solution, the purpose for which they were developed and are applied, the domain or discipline to which they apply, and the level of resolution and complexity at which they operate. As models become increasingly significant in decision making, it is important that model development and evaluation processes conform to protocols or standards that help ensure the utility, scientific soundness, and defensibility of models and their outputs for decision making. It is also increasingly important to plan and manage the process of using models to inform decision making. Computerized tools based on models certainly do not replace a participatory process in which many other factors and knowledge sources play a determining role, but allow safe and relatively cheap experimentation, and quantification of effectiveness and efficiency of different policy alternatives.

There is also an overarching category at the bottom of the Fig 1.3 used when non-market values are needed in the three categories. The tools are arranged on a time continuum based on two directions: back in time (retrospective) or forward looking (prospective, forecasting) tools.

## 1.5. Bioenergy Decision Support Systems

There are two important things which should be heeded before developing a Decision Support System. Firstly, the model builders should keep in mind the end-users and the use to which model conclusions will be put. The second advice is from Samuel Karlin of Stanford University who gave the following guidance: The purpose of models is not to fit the data, but to sharpen the questions.

Furthermore, the amount and complexity of information relating to the development of

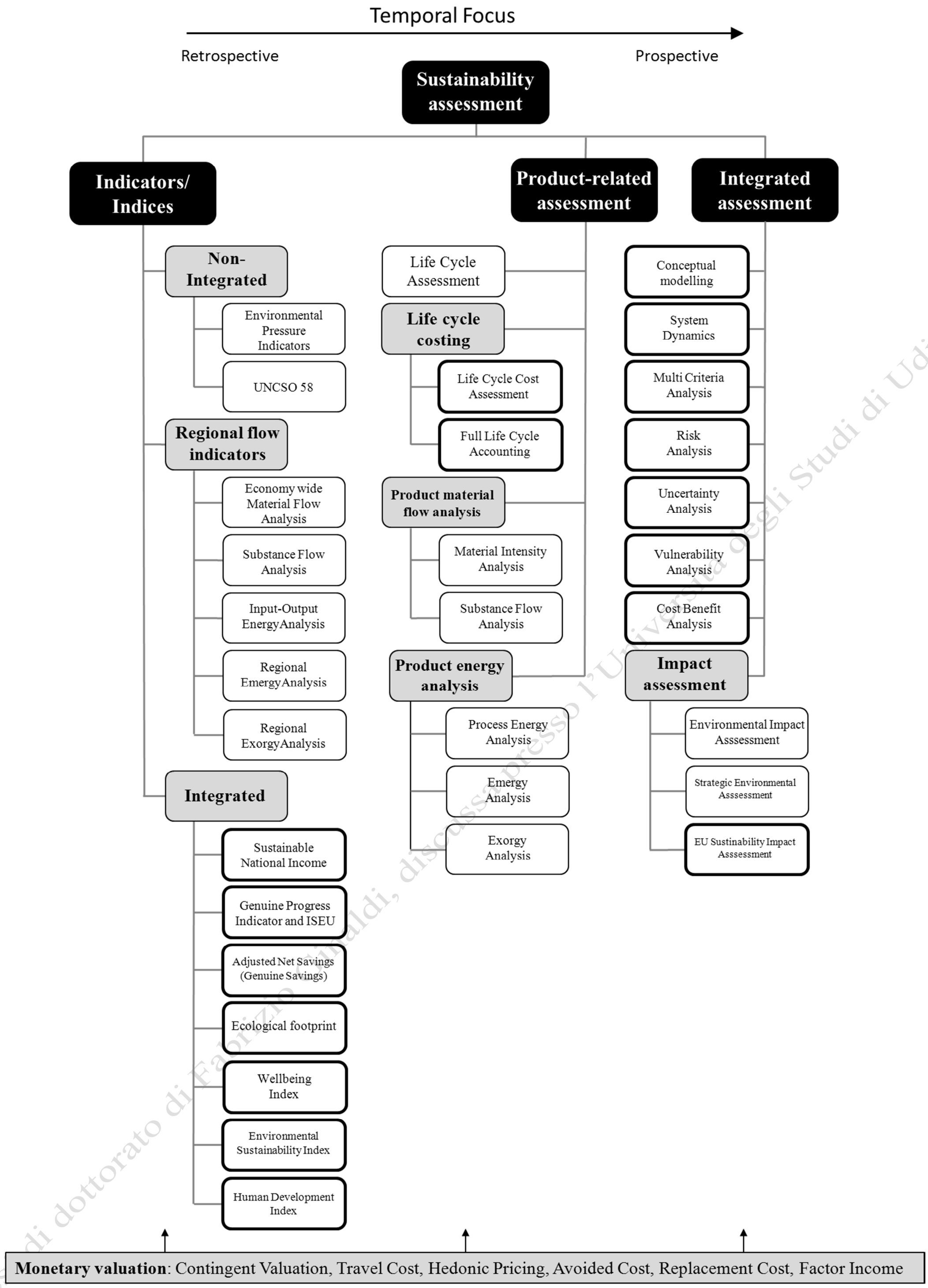


Fig. 1.3. Framework for sustainability assessment tools. The framework proposed in Ness *et al.*, 2007, is based on the temporal focus of the tool along with the object of focus of the tool. The arrow on the top of the framework shows the temporal focus, which is either retrospective (indicators/indices), prospective (integrated assessment) or both (product-related assessment). The object of focus of the tools is either spatial, referring to a proposed change in policy (indicators/indices and integrated assessment), or at the product level (product-related assessment). The monetary valuation tools on the bottom are used when monetary valuations are needed in the above tools. Thick lines around the boxes mean that these tools are capable of integrating nature–society systems into single evaluation.

bioenergy systems increases so does the problem of how to handle the information in a manner which is helpful for decision making (Mitchell, 2000). Therefore, two types of problem can be identied:

(i) how to access information about the bioenergy system and best practices for biomass production, harvesting and conversion;

(ii) how to manipulate the data and relationships about the system in order to understand and then develop bioenergy applications.

The first problem can be handled with a literature review of the available guidelines, protocols and handbooks. Solutions to the second one are found through the use of modelling techniques (deterministic or stochastic) which allow "what if" type questions to be answered.

Decision support systems link the information processing capabilities of a management information system with modelling techniques and the judgement of managers for support decision-making in unstructured situations (Dennis and Dennis, 1991). They have four main components (Alter *et al.*, 1980): (i) an interface that allows the user to interact directly with the system; (ii) a management information system (MIS) and/or a database containing appropriate and relevant information; (iii) a component that manipulates the data and information using developed relationships which allows systems to be simulated; (iv) a results screen which outputs information in a readily understandable form.

There has been a significant number of reports on the application of geographic information systems (GIS), in specific spatially explicit models, to map the availability of fuel resources with respect to the power plant or end-user facility. GIS approaches have been applied for the spatial characterization of biomass potentials, costs, supply and demand (Noon and Daly, 1996; Graham *et al.*, 2000; Voivontas *et al.*, 2001; Freppaz *et al.*, 2004; Edwards *et al.*, 2005; Ma *et al.*, 2005; Tenerelli and Carver, 2012).

Several studies have focused on energy crop potential, but no ones present tools (i.e. software) which allow easy application by an external user, as well as treatment of the climate uncertainty.

The GIS analysis are useful tools, but it poses some problems. Foremost of these is the lack of digital spatial data. This lack in itself has a spatial component, since some regions of the world have spatial data of better quality than others.

GIS are scale-dependent, and it is necessary to consider the appropriate spatial scale for addressing the problem at hand. For example, if the problem is finding the ideal location for siting a bioenergy conversion facility, very-fine-scale data are needed. There is also a necessity to balance the need for fine-resolution data, which would enhance the reliability of predictions against the increased data storage requirements and longer run times associated with fine-scale data.

Finally, for many variables of interest, one has to derive or create a spatial distribution based on some linked variable(s) for which one does have geographically explicit data.

Development of territorial models has to follow the current principles of land evaluation and answers the questions risen from new societal needs.

## 1.6. Land evaluation

Land evaluation is formally defined as 'the assessment of land performance when used for a specified purpose, involving the execution and interpretation of surveys and studies of land forms, soils, vegetation, climate and other aspects of land in order to identify and make a comparison of promising kinds of land use in terms applicable to the objectives of the evaluation' (FAO, 1976).

Land evaluation is based on six key principles:

i) Land suitability is assessed and classified with respect to specified kinds of use. Different kinds of land use may have different requirements. Likewise land use includes the broader context of production system and its biophysical and socio-economic environment;

ii) Evaluation requires a comparison of benefits obtained and inputs (labour, plant nutrients or road construction) needed on different types of land in order to assess its productive potential;

iii) Evaluation process requires a multi-disciplinary approach;

iv) Evaluation should be assessed in terms of the biophysical, economic, social and political context of the area concerned. Evaluations for unrealistic land use options should be avoided;

v) Suitability refers to use on a sustained basis. The aspect of environmental degradation is taken into account when assessing suitable land uses. Land uses that are highly profitable in the short term but cause physical limitations or hazards in the long term are classed as not suitable for such purposes. For any proposed land use, the probable consequences for environment should be assessed as accurately as possible and taken into consideration in determining suitability;

vi) Evaluation involves comparison of more than a single kind of use.

Recently land evaluation focuses on new objectives. The first is recognition of wider land functions and services. Land performs a multitude of key environmental, economic, social and cultural functions, vital for life. These functions are generally interdependent and the extent to which land performs them is strongly related to sustainability. When land is used for one function, its ability to perform other functions may be reduced or modified, leading to competition between the different functions. Land also provides services that are useful to humans and others. An example of an environmental service is carbon sequestration. The second is the growing recognition given to stakeholders, ranging from international and regional organizations, national governments, non-governmental organizations and commercial organizations to – most importantly – villages, rural communities and individual farmers and other land users. Participatory approach is very important too: surveys take throughout account of land users knowledge and views, at the start as well as at later stages (Munda, 2008).

## 1.7. Variability and Uncertainty

Variability and uncertainty (quantitative and qualitative) in information or in procedures, measures, methods or models must be evaluated and characterized (US EPA, 2003).

Variability refers to observed differences attributable to "true" heterogeneity or diversity, in modelling it concerns model parameters or input data. Because of variability, the "true" value of model parameters is often a function of the degree of spatial and temporal aggregation. Examples of variability include variation in land resources over space, fluctuations in ecological conditions, differences in habitat, and genetic variances among populations. Variability is the result of natural random processes and is usually not reducible by further measurement or study (although it can be better characterized) (US EPA, 1997). Anyway, in territorial analysis variability is not random over space, but very often exhibits spatial dependence, i.e., land characteristic value at a certain point provides information about non-sampled points nearby (Rossiter, 1996).

Uncertainty exists when knowledge about specific factors, parameters (inputs), or models is incomplete. Models have two fundamental types of uncertainty:

- Model framework uncertainty, which is a function of the soundness of model's underlying scientific foundations.

- Data uncertainty, which arises from measurement errors, analytical imprecision, and limited sample size during collection and treatment of data used to characterize model parameters. It is sometimes referred to as reducible uncertainty because it can be minimized with further study (US EPA, 1997).

Uncertainty analysis consists of evaluating quantitatively the uncertainty or variability in the model components (parameters, input variables, equations) for a given situation, and deducing an uncertainty distribution for each output variable rather than a misleading single value. An essential consequence is that it provides methods to assess, for instance, the probability of a response to exceed some threshold. This makes uncertainty analysis a key component of risk analysis (Vose, 1996). Uncertainty analysis is also closely related to the methods associated with computer experiments because it usually relies on simulations. A computer experiment is a set of simulation runs designed in order to explore efficiently the model responses when input varies within given ranges (Sacks *et al.*, 1989; Welch *et al.*, 1992). Koehler and Owen (1996) identified computer experiments' goal and they include model response optimization, model behaviour visualization, approximation by a simpler model or estimation of the average, variance or probability response to exceed some threshold.

As remarked by Koehler and Owen (1996), inputs number (variables or parameters), outputs number and model *f* speed calculation may vary enormously in applications, and these quantities will obviously play an important role in the objectives of an uncertainty or sensitivity analysis and on the adequacy of the various available methods. Some methods are thought to small numbers of model simulations (e.g. local and one-at-a-time methods, methods based on experimental designs), while others require a large number of simulations (methods based on Monte-Carlo sampling, for instance). More economical methods use has a price, and this depends on the main model properties - it may be necessary to select a number of factors smaller than desired, or more factors interactions may have to be assumed as negligible, or the investigation may be unable to detect model departures from linearity or near- linearity. It follows that some methods are well-adapted only if the model is well-behaved in some sense, while other methods are more "model-independent" (Saltelli *et al.*, 1999), i.e. more robust to complex model behaviours such as strong non-linearity, discontinuities, non-monotonicity or complex interactions between factors.

Input factors are the model components whose influence on the output is to be investigated, and they can be an uncertain or variable parameter, an input variable, a series of related input variables (annual series of daily climate variables in a given region) or a set of alternative model structures or functional relationships within a sub-module of the model.

Hereafter, the number of input factors will be denoted by *s* and the input factors will be denoted by $z_1,...,z_s$. An input scenario will be defined as a combination of levels Z = ($z_1,...,z_s$) of input factors. When several input scenarios need to be defined simultaneously, they will be denoted by $Z_k = (z_{k,1},...,z_{k,s})$, where subscript *k* identifies the scenarios. Uncertainty analysis can answer the question "What is the uncertainty in the model response $\hat{Y}= f(Z_k)$ [1.1] given the uncertainty in its input factors?" This type of analysis consists of four steps:

i. Definition of uncertain input factors joint distribution (taking into account also correlations among factors).

ii. Generation of *N* scenarios of input factors $Z_k = (z_{k,1},...,z_{k,s})$, $k = 1,...,N$.

iii. Model output computation for each scenario, $f(Z_k)$, $k = 1,...,N$.

iv. Output distributions analysis (computation of means, variances, quantiles, probability distribution, etc).

## 1.8. Aim and outline of this thesis

This thesis analyses two different agro-energy chains: the short chain, where farms use own produced Straight Vegetable Oil (SVO) to obtain energy by cogeneration, and the medium/long chain where farmers (who supplies the biomass) and processors (that convert it into biofuel) are organized in a cooperative way.

The two systems are organized on different spatial scales; consequently, their analysis requires different approaches. In both cases, the focus of this work is support decision makers in the policy definition process. Short chain has been analysed by a product related tool (LCA) to compare energy crop performances whereas medium/long chain planning required a more integrated approach. Land agro-energy planning has to summarize territorial, climate, logistic information to compare economic, energy and environmental results of alternative crop management scenarios. Crop simulation model is particularly indicated to treat all this complexity in an integrated way (Wallach *et al.*, 2006). Cropping system analysis needs also to take into account climate uncertainty. In order to completely explore the climate variability of an area it is necessary the application of weather generator tool. So, the second chapter describes implementation

[1.1] The hat notation is used to indicate that the value is an estimate and validation of *Climak 3* weather generator. In the reported article, the author of the thesis was in particular involved in the development of tools for the stochastic weather generator evaluation and validation. Annex II proposes a new methodology to solve weather generator comparison problem.

Chapter three's first goal is to analyse and assess energy and environmental sustainability of first generation biofuels cultivation using the LCA methodology. It compares the impacts of the SVO production from rapeseed, sunflower and soybean crops, cultivated with different (high and low) input, with the production of fossil fuel (diesel). In addition, the analysis was extended to the comparison of final electricity production impacts through CHP (Combined Heat and Power) small power plants fuelled by vegetable oils, derived from crops obtained by a local agricultural production, by fossil fuel (diesel) and Italian mixed electricity production.

Chapter four moves the focus on a broader scale. This research proposes an integrated and interdisciplinary approach for planning biofuel supply chain at a regional level aimed i) at evaluating land potential use for energy production and the related side effects and ii) at supplying the existing processing plants accomplishing with the economic, energy and environmental targets. The problem of biomass allocation is dealt by integrating the territorial and climatic information in a crop simulation model (*MiniCSS*; Rocca and Danuso, 2011). The approach is based on the simulation of agricultural and environmental variables affecting crop yields, production technologies and related costs. Moreover, this methodology uses an optimized product flows from farm to collecting points and processing plants and evaluates the risk caused by price volatility. At first, dynamic crop simulation takes into account climate variability; in later stages the results are used in a routine to optimize transports along existing road network. Finally, the procedure creates a global suitability index for the whole biofuel chain. This index evaluates bioenergy crops sustainability on the territory combining economic, energy and environmental results.

Chapter five's aim is to develop a software application to plan supply chain at a regional level and easily compare alternative scenarios using the approach aforementioned.



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# 2

# Evaluation of climate uncertainty affecting cropping scenario:

## Implementation and validation of *Climak 3* weather generator

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The author of this thesis contributed to this work developing tools for stochastic weather generator evaluation and validation.

## 2.1. Abstract

Weather generators (WG) are stochastic models, which generates series of weather data of indefinite length with statistical properties similar to those of the original series. WG have been extensively used in different biophysical models, providing them with meteorological input data. *Climak 3* is a new version of *Climak* (Danuso, 2002), capable to generate daily meteorological data of precipitation, minimum and maximum air temperatures, solar radiation, reference evapotranspiration and wind speed. The performance of *Climak 3* was tested using meteorological datasets coming from different locations over the world. The results for Italy, Bulgaria and Argentina are presented and discussed.

**Keywords**: Weather Generators, Stochastic Models, Validation, Climate Change

## 2.2. Introduction

Climate is one of the main factors which affect human activities and different ecological processes. Great efforts have been devoted to weather forecasting investigations. The study of the climate statistical properties has allowed the development of climatic stochastic models (weather generators) for the generation of weather data (Jones at al., 1970; Richardson, 1981; Larsen and Pense, 1982; Shu Geng *et al.*, 1985; Richardson and Nicks, 1990; Semenov *et al.*, 1998; Donatelli *et al.*, 2005; Donatelli *et al.*, 2009; Birt *et al.*, 2010). Weather generators (WG) are stochastic models, which produce meteorological data of indefinite length, on the basis of climatic parameters estimated from historic meteorological data series. Application of weather generators allows Monte Carlo simulations to obtain probability distributions of agro-ecological variables related to climate, spatial interpolation of the climate parameters (thus obtaining data for locations not covered by meteorological stations) and assessment of environmental scenarios depending on climatic changes.

In this paper the third version of the *Climak* (Danuso and Della Mea, 1994; Danuso *et al.*, 2011) weather generator is presented. *Climak* was developed in the early '90s and provided significant results (Acutis *et al.*, 1999; Danuso, 2002). Initially *Climak* generated daily data of precipitation, maximum and minimum temperatures, solar radiation and evapotranspiration. The new version (*Climak 3*), developed jointly with the weather generator CLIMA (Donatelli *et al.*, 2005; Donatelli *et al.*, 2009), allows also the generation of wind speed data. This version has been developed and implemented using the SEMoLa language (Danuso, 2003). To validate *Climak 3*, generated meteorological data series were compared with the historical ones.

## 2.3. Materials and Methods

### 2.3.1 Model description

*Climak 3* has a structure similar to other weather generators (Jones at al., 1970; Richardson, 1981; Larsen and Pense, 1982; Shu Geng *et al.*, 1985; Richardson and Nicks, 1990; Semenov *et al.*, 1998; Donatelli *et al.*, 2005; Donatelli *et al.*, 2009; Birt *et al.*, 2010). It generates daily total precipitation (*Prec*), daily minimum and maximum air temperatures (*Tmin*, *Tmax*), daily integral of solar radiation (*Rg*), evapotranspiration (*ETr*) and daily wind speed (*Winds*) (Tab. 2.1). For the evapotranspiration, this could be generated from real measured evapotranspiration or from calculated potential or reference

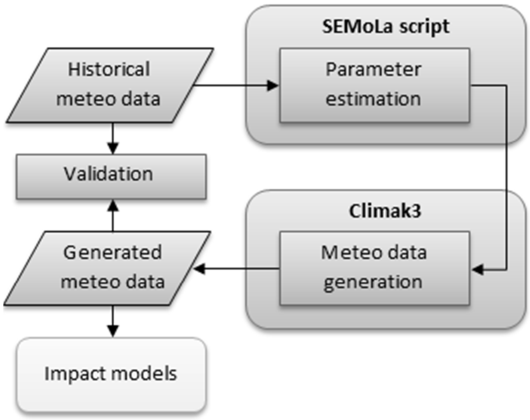



Fig. 2.1. Application of the *Climak 3* weather generator.

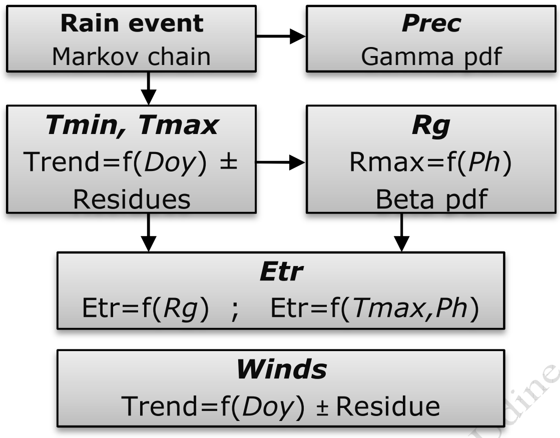



Fig. 2.2. Procedure of generation of meteorological variables.



evapotranspiration (Allen *et al.*, 1998), depending on which type of evapotranspiration parameters have been estimated. The weather generation procedure consists of 1) estimation of climatic parameters from historical meteorological data, and 2) data generation based on the statistical parameters obtained (Fig. 2.1). In *Climak 3* precipitation are not distinguished between solid (hail, snow) and liquid (rain) precipitation.

As a first step, *Climak 3* generates the occurrence of rainy or dry day by a first order Markov chain and the rainfall amount, if the day is rainy. After rainfall generation, the minimum and maximum temperatures are generated separately, considering the status of the day (rainy or dry):

$$Temperature = Trend + Residue$$

where *Trend* is an average daily minimum/maximum temperature for the dry/rainy days, obtained as a function of the date, by interpolating a second order Fourier series. Solar radiation is obtained from the astronomical photoperiod (Ph) and from the daily thermal excursion using the method described in Keisling (1982). The evapotranspiration is generated from the solar radiation data (Doorembos and Pruitt, 1977); if data of solar radiation are not available, evapotranspiration is obtained from photoperiod and maximum temperature. In the end, wind speed values are generated (Fig. 2.2). Wind speed variability has been often expressed using Weibull density function (Takle and Brown, 1977; Weisser and Foxon, 2003; Aksoy *et al.*, 2004; Bhattacharya, 2010). This approach is applied widely and considered as a standard. Despite this, Weibull probability density function is not able to properly represent the minimum values of wind speed

(Weisser and Foxon, 2003). Moreover, this approach is not able to correctly describe the annual trend and the monthly distribution of the historical data. To address these limitations, in *Climak 3*, a new approach for generating wind speed data was implemented.

In the weather generator, different types of pseudo-random number generators can be used: a simple but faster LCG (linear congruential generator) or the Mersenne Twister series (32, 53 or 64 bit) having a longer period (Matsumoto and Nishimura, 1998). The 32 bit Mersenne Twister pseudo-random number generator has a period of ($2^{19937}$-1). The procedures for parameter estimation and model validation are implemented as scripts of the SEMoLa framework (see Annex I). Both are completely open, easy to modify and freely available.

### 2.3.2. Case study

The performance of *Climak 3* was evaluated using meteorological datasets from different locations of Europe and South-America. Relatively long records of daily weather variables (minimum and maximum air temperature, precipitation, solar radiation, evapotranspiration) were provided by Joint Research Center (EU) and Regional Meteorological Service of the Friuli Venezia Giulia region (OSMER). Wind speed data were available only in datasets from Italy. This data allowed to test *Climak 3* performance


Fig. 2.3. Study areas geographical position.

Tab. 2.2. Geographical coordinates and elevation of the study areas.

| State/Region | Latitude (°) | Longitude (°) | Elevation, m a.s.l. | Ecoregion division |
|---|---|---|---|---|
| Italy, Friuli V.G. | 46.00 | 13.00 | 100 | Mediterranean |
| Bulgaria, Vratsa | 43.23 | 23.52 | 115 | Moderately continental |
| Argentina, La Pampa | -36.25 | -63.50 | 119 | Subtropical |

in different climatic conditions. In this paper, results for Mediterranean, moderately continental and sub-tropical austral climates are presented. The datasets from meteorological stations of Italy, Bulgaria and Argentina were used (Fig. 2.3). The chosen sites are characterized by different climatic/meteorological conditions (Tab. 2.2). The number of years of the data ranged from 10 for Italy to 20 for Argentina and 35 for Bulgaria.

### 2.3.3. Validation

The goodness of generated weather data depends on the model itself and the quality of the parameters estimation. This, in turn, depends on the calculation methods and on the number of years of historical data available. Weather generators are supposed to generate synthetic weather series with statistical properties similar to the observed ones (Semenov *et al.*, 1998; Donatelli *et al.*, 2005). This means that: (i) means and variances of daily synthetic weather data are to be not significantly different from those of observed series, (ii) means and variances of monthly values of the weather variables from synthetic and observed series are to be comparable, (iii) synthetic weather series are to follow the probability distribution statistically not different from the historical ones.

To test the performance of *Climak 3* a validation procedure has been developed. The procedure consists of different graphical analysis evaluating the correspondence of historical and generated data (Semenov *et al.*, 1998; Hayhoe, 2000; Birt *et al.*, 2010), comparing monthly means and monthly standard deviations of all meteorological variables. Rainfall was also compared using relative frequency histograms. Cumulative probability functions were used for graphical representation of the correspondence between historical and generated data distribution.

Validation was performed using generated datasets of 100 years. A long synthetic series provided stable statistical properties thus ensuring that any significant difference between the observed series and the synthetic series is not a result of sampling, as the observed series is only a part of the 'real' stochastic process (Qian *et al.*, 2004).

Quantile-quantile (QQ) plots are also used to demonstrate visually how well the generated series followed the probability distribution of the observed series (Qian *et al.*, 2004), for daily minimum and maximum temperature, radiation, wind speed and precipitation. Rain data include only the values between the $10^{th}$ and the $90^{th}$ quantile of the distribution to not consider extreme values.

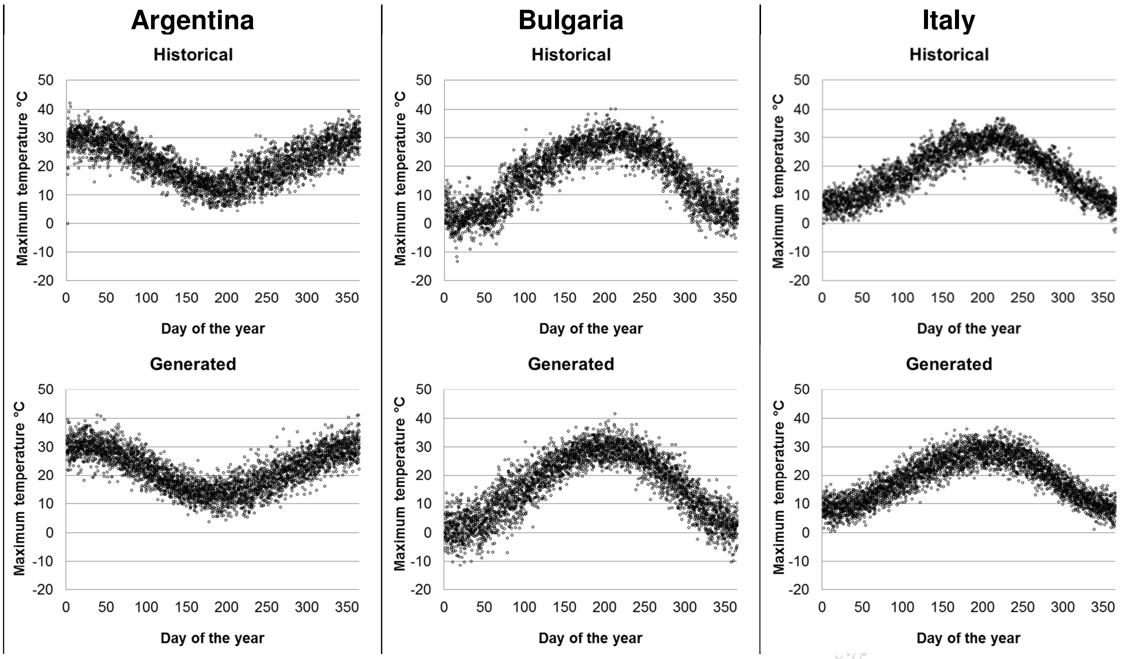



Fig. 2.4. Daily maximum air temperature (°C) for historical and generated data for Argentina, Bulgaria and Italy.

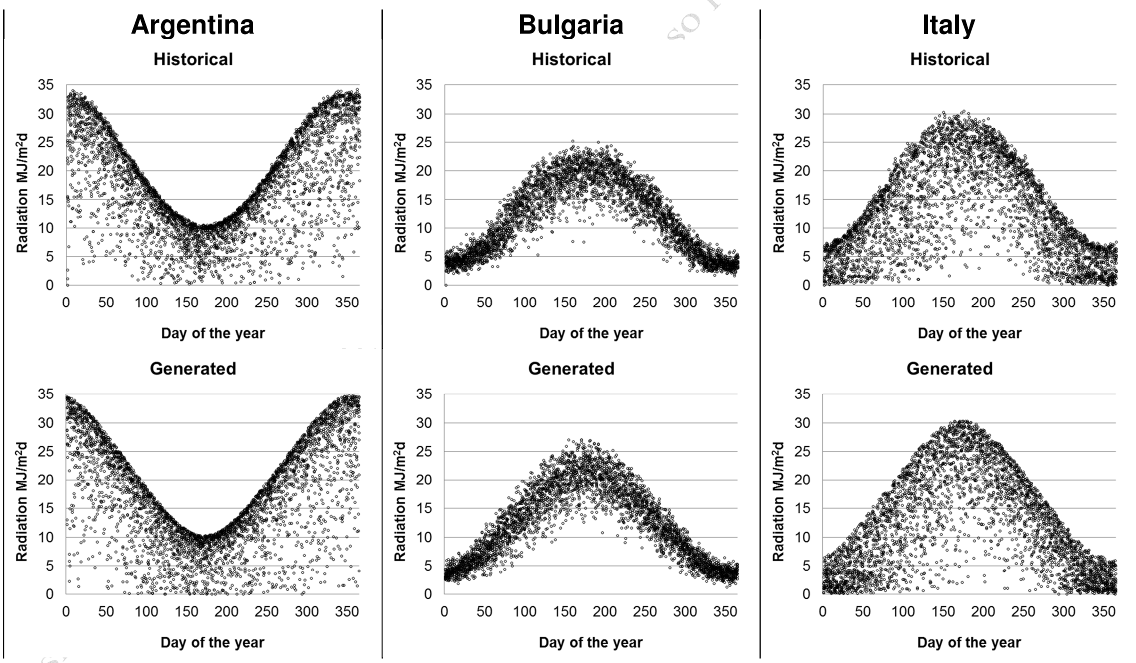



Fig. 2.5. Daily solar radiation (MJ/m$^2$d) for historical and generated data for Argentina, Bulgaria and Italy.

## 2.4. Results and Discussion

Using *Climak 3*, meteorological datasets for different locations were generated. It was expected that the software implementation of *Climak 3* would provide realistic output data for different climatic conditions. In figure 2.4, 2.5 and 2.6 the results for Italy,

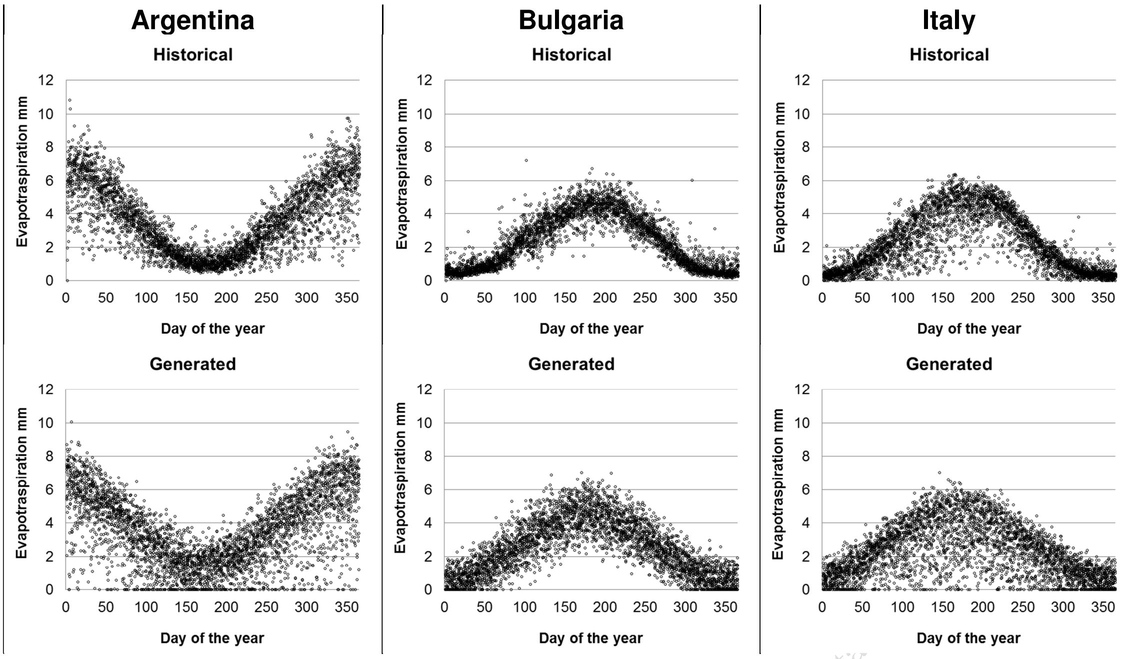



Fig. 2.6. Daily reference evapotranspiration (mm) for historical and generated data for Argentina, Bulgaria and Italy.

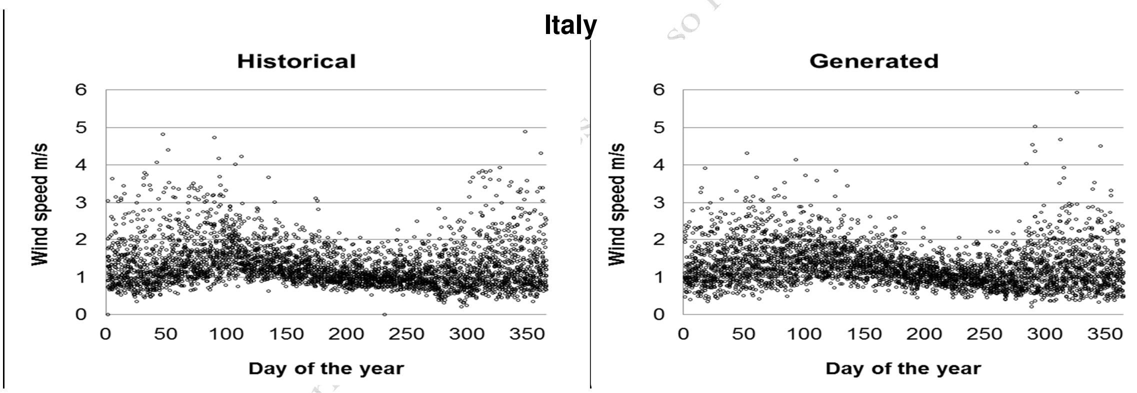



Fig. 2.7. Daily average wind speed (m/s) of historical and generated data for Italy (Pordenone, Friuli Venezia Giulia region).

Bulgaria and Argentina are presented. In figure 2.7 historical and generated data of wind speed (m/s) are presented only for Italy. From these figures of daily data comparison it is possible to notice that *Climak 3* gives satisfactory results. In general, the annual trend of all variables is followed. However in the generated data there is a slight overestimation of the evapotranspiration standard deviations, which can be neglected since the difference between values does not exceed 1 mm.

Results of monthly means and standard deviations comparison of meteorological variables are presented in figures 2.8, 2.9, 2.10, 2.11, 2.12. These figures confirm a good fitness of the synthetic and historical data, thus proving a good performance of *Climak 3* in generation of mean values and variability, though there is a slight shift, especially

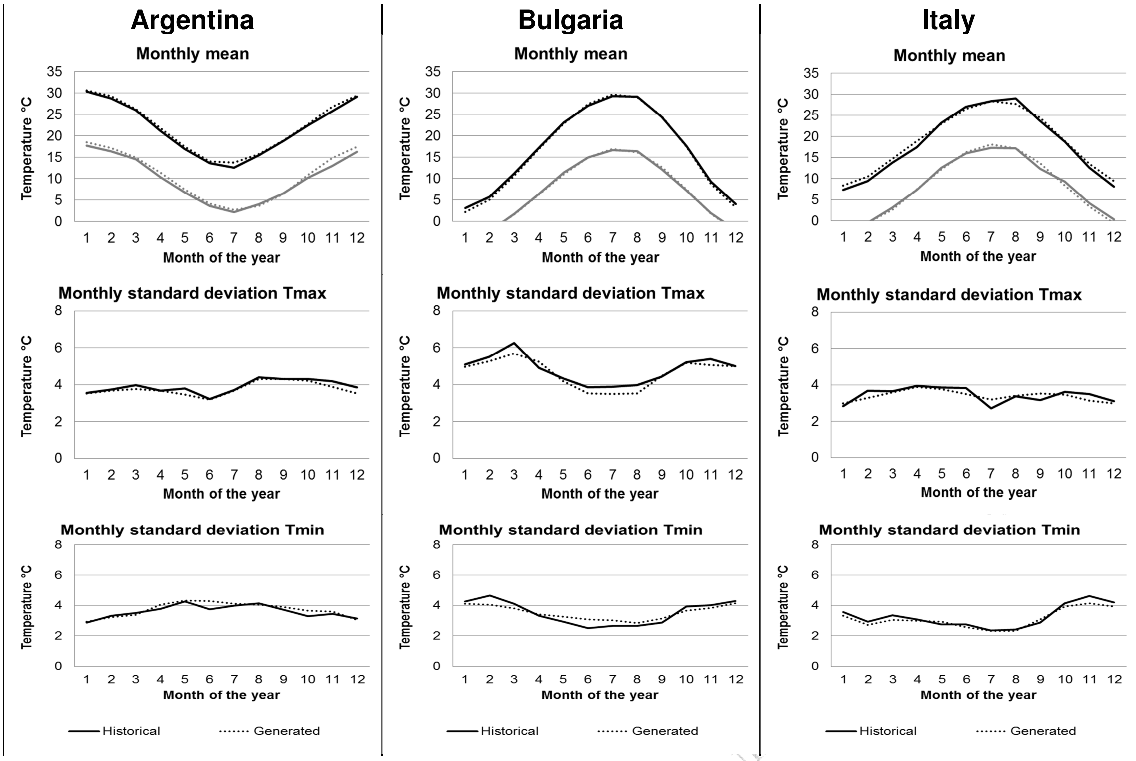



Fig. 2.8. Monthly mean and standard deviation of maximum and minimum temperatures (°C) for historical and generated data for Argentina, Bulgaria and Italy.

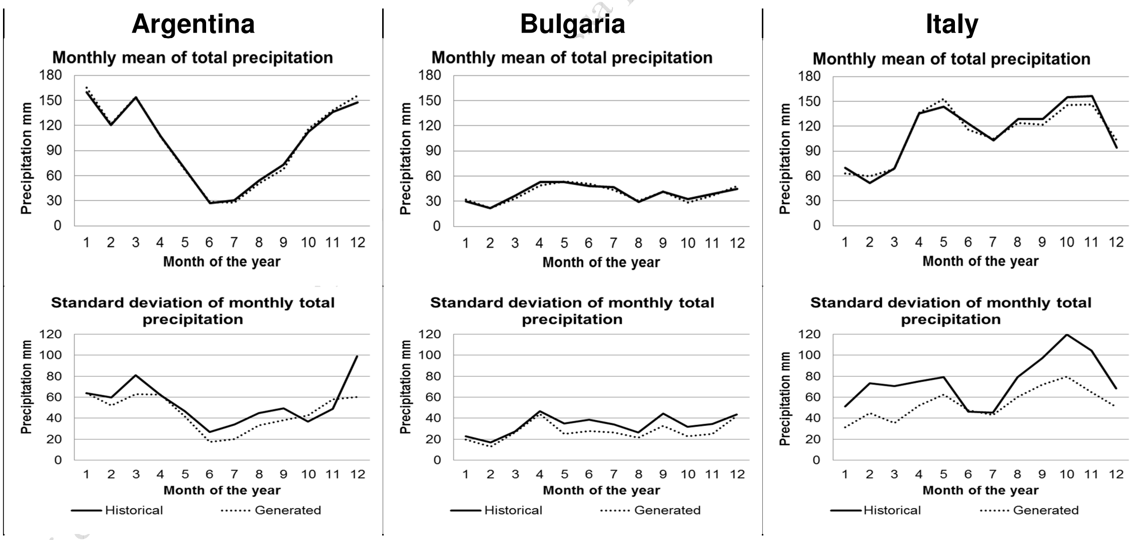



Fig. 2.9. Monthly mean and standard deviation of precipitation (mm) of historical and generated data for Argentina, Bulgaria and Italy.

when representing rain and evapotranspiration variability. In Fig. 2.13 precipitation frequency histograms are presented.

From the Fig. 2.14, where cumulative distributions of maximum, minimum temperatures and precipitation for January and July are reported; it is possible to notice that in January for both hemispheres, variation ranges of maximum and minimum

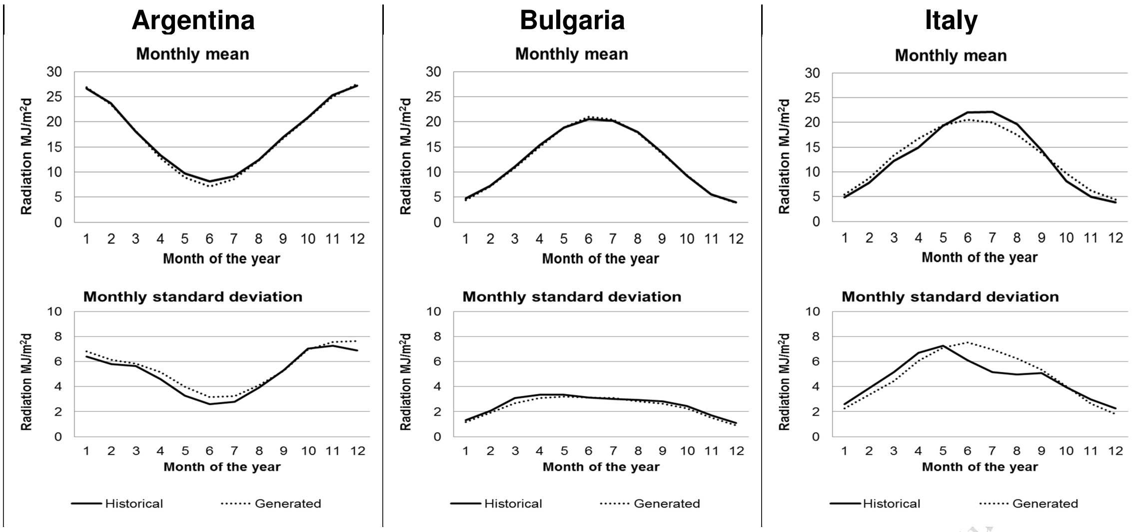



Fig. 2.10. Monthly mean and standard deviation of solar radiation (MJ/m2) of historical and generated data for Argentina, Bulgaria and Italy.

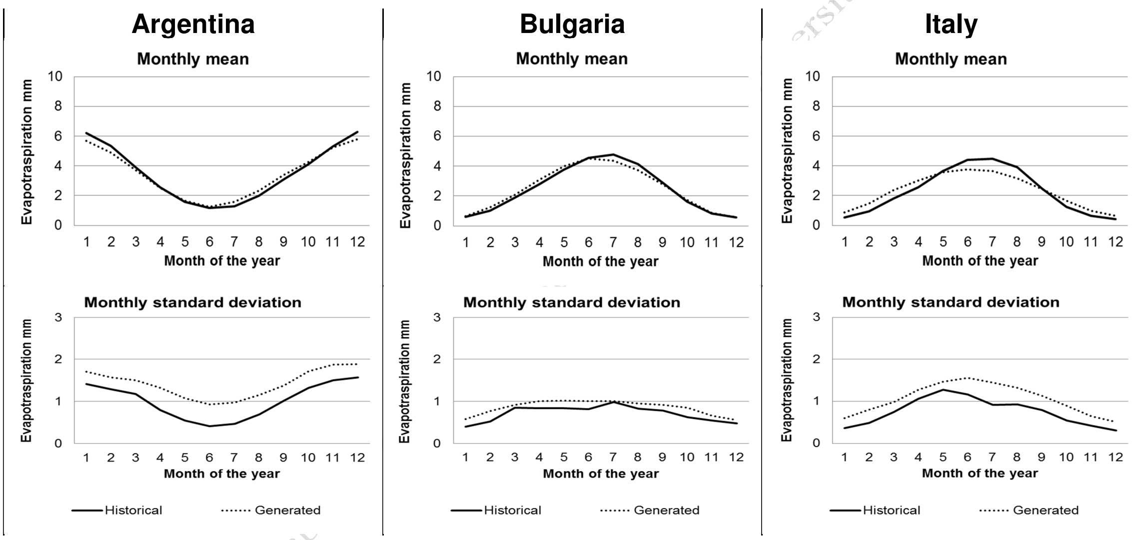



Fig. 2.11. Monthly mean and standard deviation of reference evapotranspiration (mm) for historical and generated data for Argentina, Bulgaria and Italy.

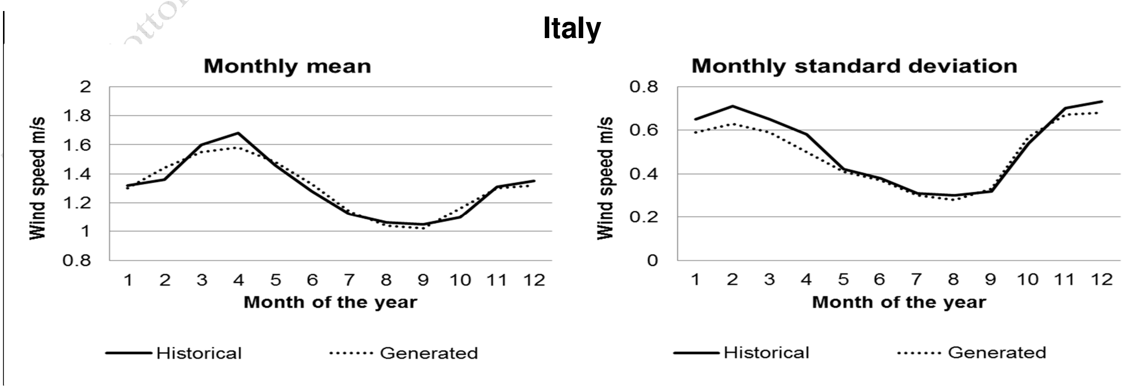



Fig. 2.12. Monthly mean and standard deviation of wind speed (m/s) for historical and generated data for Italy.

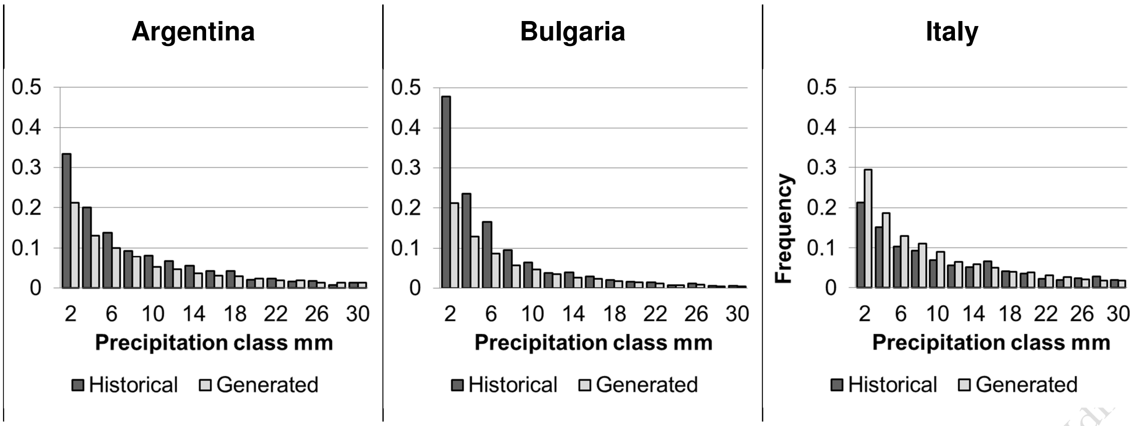



Fig. 2.13. Precipitation frequency histograms (mm) for historical and generated data for Argentina, Bulgaria and Italy.

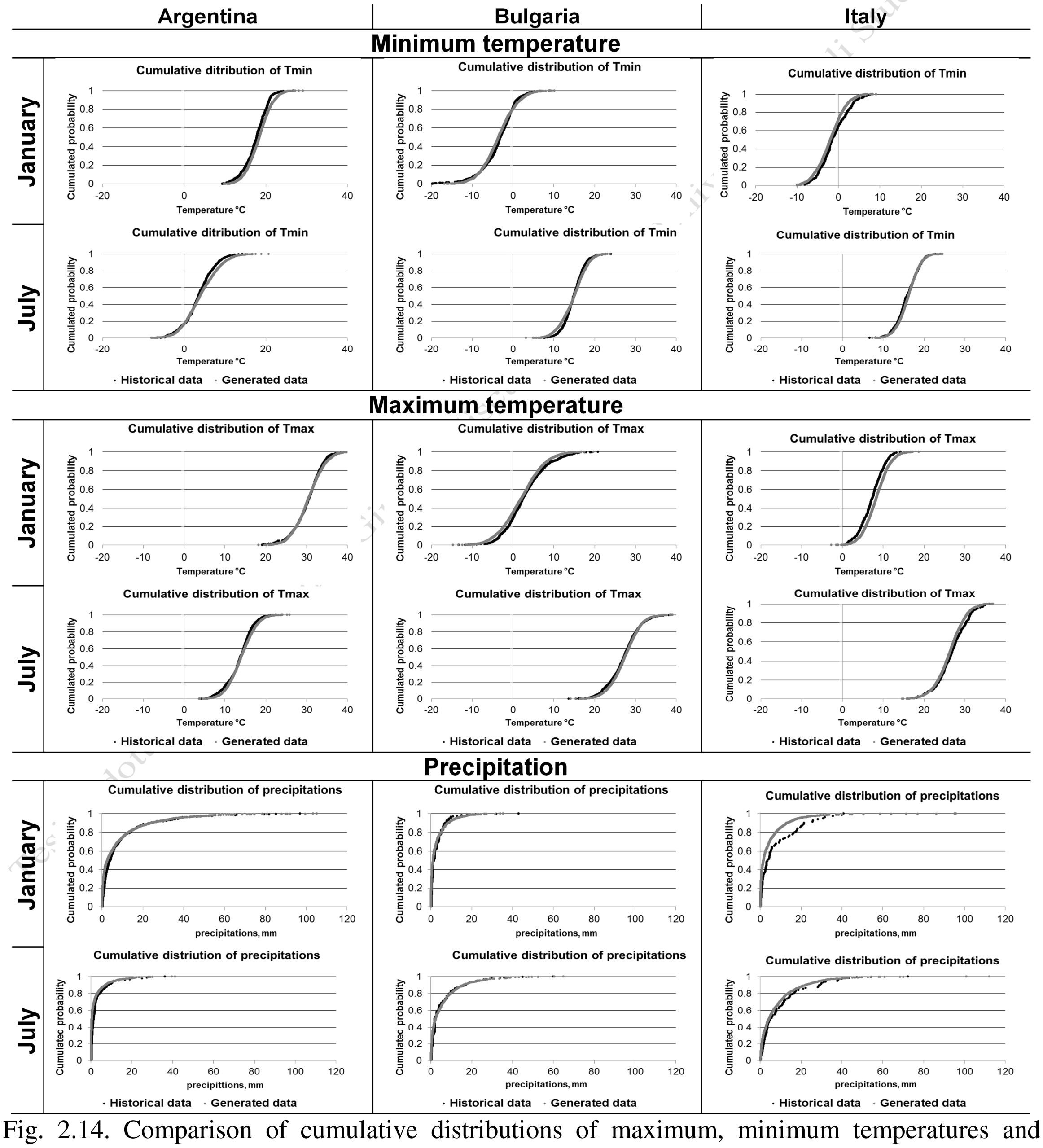
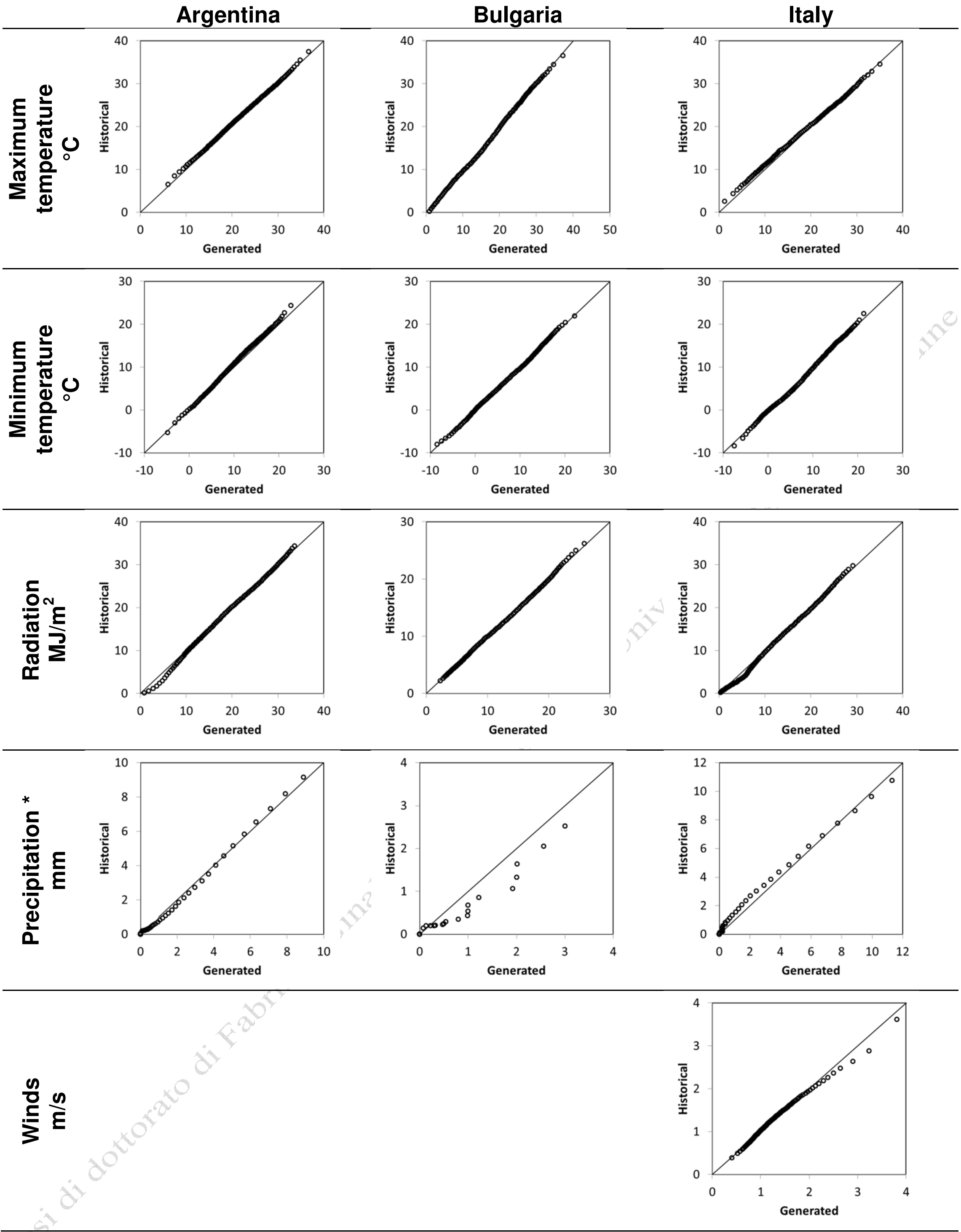



Fig. 2.14. Comparison of cumulative distributions of maximum, minimum temperatures and precipitation for historical and generated data (only for the months of January and July) for Argentina, Bulgaria and Italy.




* Precipitation include only the values between the 10th and the 90th quantile of the distribution.

Fig. 2.15. Quantile–quantile plot of maximum, minimum temperatures, radiation, precipitation and wind for historical and generated data for Argentina, Bulgaria and Italy.

temperatures of the observed data is wider than those of generated ones.

In Fig. 2.15 the QQ plots are represented for daily minimum and maximum temperature, radiation, wind speed (only for Italy) and precipitation.

## 2.5. Conclusions

The goodness of a weather models basically depends on the model structure itself, on methods and algorithms applied for parameter estimation and on algorithms for data generation (sampling from probability distribution function).

Validation results obtained show that *Climak 3* can be considered as sufficiently accurate tool for the generation of meteorological data in temperate and cold climates. In general, the behavior of the model has been satisfactory but some aspects are still to be improved. A new version *Climak 4* is now under development that will address these limitations introducing new algorithm for temperatures and radiation. The further works will be focused on the improvement of the estimation and/or generation procedures of evapotranspiration and radiation data, and on a better representation of the *Tmax* and *Tmin* variability. Moreover, it will be necessary to develop issues concerning downscaling of meteorological variables and the generation of extreme events, especially for precipitation and wind speed. In fact, wind speed model, at present, is not able to represent high speed values, observed in some locations.

Furthermore, a stand-alone application tool with easy to use graphical interface (Climak WG) is being developed in order to allow a simpler use of the weather generator.

Future developments will include also the generation of hourly data (Fatichi *et al.*, 2011.

Parameter estimation script, generation model and validation procedure are freely available from authors. The executable and source code of *Climak 3*, the script for the parameters estimation and that for the validation procedure are freely available from the web (http://www.dpvta.uniud.it/~Danuso/docs/Climatica/Climatica_Home.html).

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## List of Abbreviations

| | |
|---|---|
| *Doy* | Day of the year |
| *ETr* | Evapotranspiration (mm) |
| *Pdf* | Probability density function |
| *Ph* | Photoperiod |
| *Prec* | Daily total precipitation (mm) |
| *QQ* | Quantile-quantile |
| *Rg* | Daily solar radiation (MJ·m$^{-2}$) |
| *Tmax* | Daily maximum air temperatures (°C) |
| *Tmin* | Daily minimum air temperatures (°C) |
| *Winds* | Daily wind speed |
| *WG* | Weather generators |

# 3

Evaluation of the short energy chain (farm level):

## LCA of Straight Vegetable Oil production and use for cogeneration in a small/medium farm in North-Eastern Italy



**Article in preparation**

## 3.1. Introduction

The worldwide emission increase has forced the implementation of policies and regulations aimed to reduce greenhouse gases (GHG) rates. The current European legislation (European Commission, 2009) has imposed as mandatory national targets for 2020 the use of energy from renewable sources (for Italy 17 % of gross final energy consumption should be accounted for renewable sources energy). The directive has set specific target for the transport sector (10 % of the consumed energy) and new sustainability criteria for biofuels to be considered to reach national goals and receive national and local financial supports. The 10 % of the energy consumption in Italy by the transport sector in 2009, was about 4.2 Mtoe whereas biofuel consumption about 1.2 Mtoe (European Commission, 2011). The replacement of fossil fuels with renewable energy (biofuels, hydrogen and electricity) will be achieved in the transport sector primarily by the use of first-generation biofuels, presently the only direct fossil fuel substitute available on a significant scale (European Commission, 2007). At the end of 2011 almost the whole Italian biofuel production was composed by biodiesel with production capacity of 2.4 Mt (USDA, 2012).To achieve the greatest supply security, it is necessary to combine the domestic production with imports and treat first-generation biofuels as a bridge for the second-generation, which is up to now not yet commercially available and more expensive than first-generation. However, all this, will lead to increase of the domestic production of vegetable oil, as well as increment of the surface under three main oilseed crops already cultivated in Italy (soybean, rapeseed and sunflower), and today covering less than 300.000 ha (Istat, 2012). As reported by the annual plan for Italian Renewable Energy Action Plan of 2010, the pure vegetable oil per se, as bioliquid and not only as a basic raw material for biodiesel, will make a substantial contribution to bioenergy, both to the production of electricity (4.86 TWh in 2020, corresponding to 5 % of total electricity provided by all sources of renewable energy) and for the heating and cooling (150 ktoe again in 2020, equal to about 1.5 % of all renewable energy sources). Recently, following the changes of the incentive system, the introduction of new tariff and the clarifications regarding the use of short chains and traceability, pure vegetable oils have assumed a primary role in the whole national electricity generation, especially at a small-scale production of electricity for specific uses, related to the local agricultural production (short-chain). In this context, it is of interest to study the small-scale production of biofuels for specific uses, such as small-scale produced Straight

Vegetable Oil (SVO) for agriculture self-supply. This study proposes the use of SVO to close the cycle of local agricultural production. SVO is a biofuel obtained from plant seed oil pressing and can be used as biofuels in CHP small power plants to generate simultaneously both electricity and heat, using an adapted diesel engine with minor modifications in the fuel intake system, as already proved in other countries (Esteban *et al.*, 2011).

The local development of chains for the production of first-generation biofuels would be an opportunity for Italian agriculture, but at a large scale production, especially using annual crops, could trigger to some negative environmental effects related to $CO_2$ emissions (Russi, 2008; Fazio and Monti, 2011). For these reasons, the UE has set a number of criteria designed to ensure the compliance of biofuels production with environmental, social and economic sustainability goals. In this sense, the 2009/28/EC Directive plans to reduce emissions of GHG per unit of energy, produced during the entire life cycle, at least by 35 %, rising up to 50 % and 60 % in 2017 and 2018, respectively.

The first objective of this study was to analyse and assess, using the LCA methodology, the energy and environmental sustainability of the cultivation of first generation biofuels, in particular, comparing the impacts of the SVO production from rapeseed, sunflower and soybean crops, cultivated with different (high and low) input, with the production of fossil fuel (diesel).

In addition, the analysis was extended to the comparison of the impacts caused by the final electricity production trough CHP (Combined Heat and Power) small power plants fueled by vegetable oils, derived from the crops obtained by a local agricultural production, by fossil fuel (diesel) and the Italian mixed electricity production.

## 3.2. Methodology

The study is consisted of three steps, where the first two ones are essential to build LCA inventory, one of the main phases within LCA methodology:

1) Identification of the most common agricultural techniques for oilseed crops in NE Italy and their yields for two input classes (high and low);

2) Identification of the typical chain for the production of pure vegetable oil and its application to generate both electrical and thermal energy in a small/medium farm on the study area;

3) Life Cycle Assessment (LCA) of the production of vegetable oil and electricity with cogeneration.

### 3.2.1. LCA methodology

Life Cycle Assessment (LCA) is a standardized method (UNI EN ISO 14040 norms), applied to agricultural and industrial systems, to evaluate the product life cycle from cradle to grave or from cradle to gate. It is an objective method to evaluate and estimate energy and environmental impact linked to a product, process or activity throughout all phases of its life cycle, from mining to the end of life (from resources consumption to hazardous substances emission).

The LCA concept consists of four major steps: 1) Goal and scope definition, 2) Life Cycle Inventory of systems inputs (materials, energy, natural resources,…) and outputs (emissions, waste,…) 3) Assessment of the input and output flows impacts and their significance, 4) Results interpretation and definition of action guidelines.

#### *3.2.1.1. Goal and scope definition*

The first objective of the LCA in this study is to quantify and compare the environmental and energy demand of the crop of sunflower, rapeseed and soybean, cultivated with high and low input, in an area of North East of Italy, with the aim to evaluate their potential use as energy crops for first generation biofuel (SVO, straight pure oil), in comparison with the production of fossil fuel (diesel).

Additionally this study includes SVO production and its use, as fuel, in CHP (cogeneration, combined heat and power) small power plants, as occur in the small-scale agricultural production system for energy self-supply. In this case the analysis is extended to study the impacts caused by the final electricity production trough small CHP and by fossil fuel (diesel) in comparison with the Italian mixed electricity use.

More specifically the study was focused on the identification of the environmental burden of the oil production on which is most convenient operate to obtain the most significant reduction of environmental impacts.

In order to fully investigate the system, the crop scenarios for each oilseed crop (rapeseed, sunflower and soybean) were analyzed considering different functional units as reference. Each functional unit represents a different point of view on the system. In this sense four types of comparison were performed between:

1) yields of the three energy crops cultivated with two different agricultural techniques (with high and low level of input), considering the hectare as functional unit;

2) production of grain that allow to obtain 1 t of oil – with the kilograms of produced grain corresponding to a 1 t of oil as functional unit;

3) production of vegetable oil and diesel corresponding to a 1 GJ of Lower Heating Value (LHV) – with the kilograms of oil produced and diesel equal to a 1 GJ of LHV as functional unit;

4) the production of 1 kWh obtained by cogeneration powered with SVO, diesel and by the Italian electricity mix - with the kWh as functional unit.

*System boundaries*

LCA from cradle-to-farm gate of short agro-energy chain has been performed. The life cycle of each input for crop, oil and energy production is included in the system boundaries, considering raw material extraction, input production, transport, use, maintenance and disposal/discovery (Fig. 3.1).

The analysed system (foreground) is composed by three elementary processes (sub-systems): crop production, oil production by pressing and energy production through cogeneration. Each sub-system includes the production process itself, its input requirements and yields. Data of agricultural inputs and seeds yields, used for LCA inventory, are representatives of the most widely used practices of the rapeseed, sunflower or soybean cultivation in study area. The chain ends with SVO utilization in CHP unit inside the farm.

The analysis took into account the products extracted from the system and the emissions to air, water and soil due to human activities (e.g. $N_2O$, nitrates, ammonium, pesticides, diesel combustion).

The fossil energy supply, compared with that deriving from the vegetable oil, includes the production of crude oil, its refining, transportation of product from the refinery to the farm and related emissions. Italian electricity mix considers also production process and its distribution to farm.

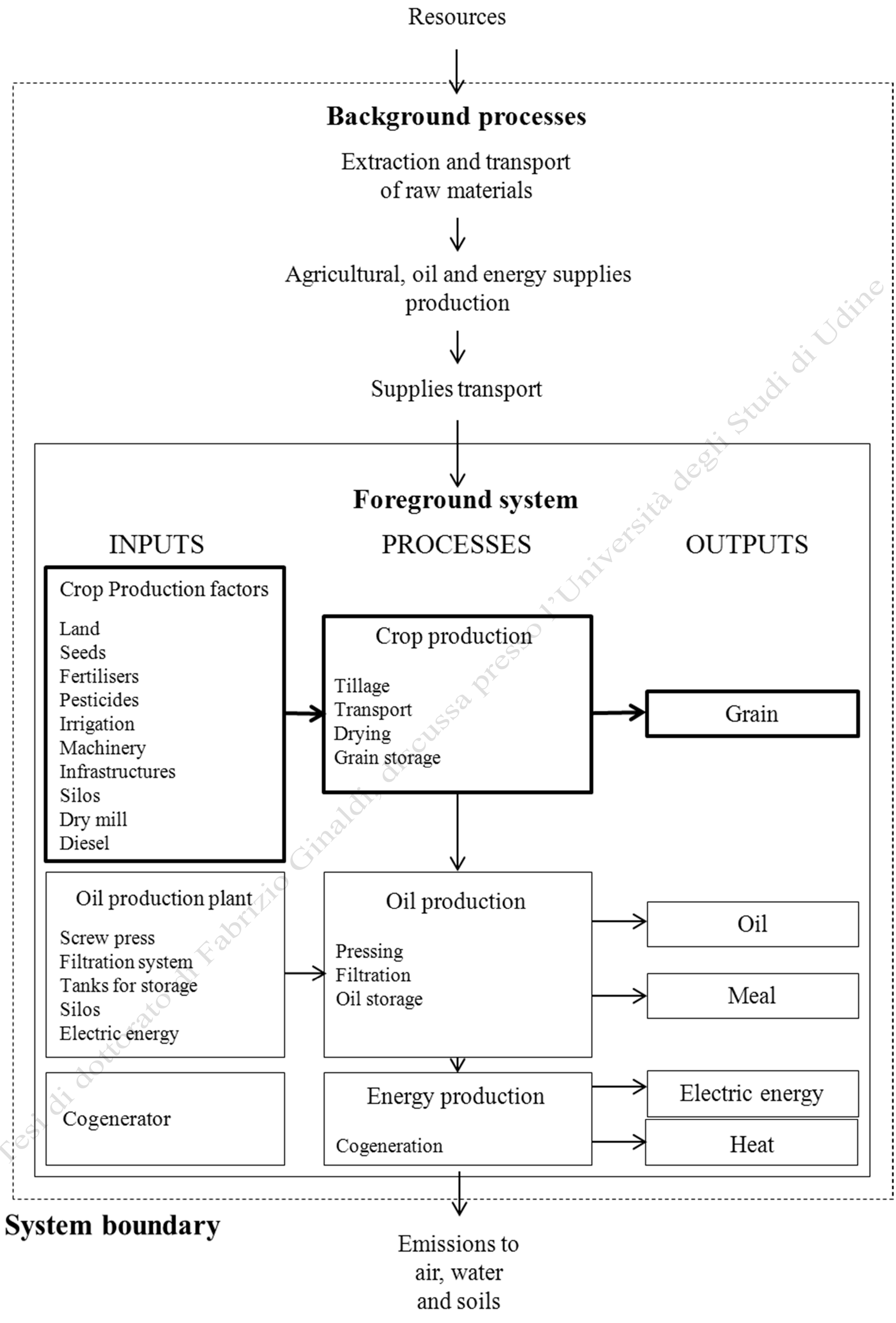




Fig. 3.1. Scheme of the short agro-energy chain system for the production of vegetable oil and its subsequent conversion in energy by cogeneration. Highlighted the crop production sub-system.

*3.2.1.2. Life Cycle Inventory*

LCA for primary sector must take into account great variability arising from the different pedo-climatic conditions in time and space. In order to reduce the latter type of variability, this study was performed on a limited area with similar pedo-climatic features, the North-East Italy.

The study involves background processes for production and transport of inputs for the three distinct sub-systems. All information regarding raw material extraction, production, transport, use, maintenance and disposal of inputs are contained in libraries of Ecoinvent database 2.1 (Nemecek and Kägi, 2007) and referred to european cropping systems.

A farm with 9.8 $m^2$ of UAA (Usable Agricultural Area), the average dimension for a farm in North East Italy (Friuli Venezia Giulia Region, 2012), was considered as model for plants sizing. It has a screw press and an endothermic engine with cogeneration fuelled with standard pure vegetable oil (as defined in DIN 51605, 2010).

The inventory compilation is presented separately for each of the three sub-systems highlighting specific process emissions.

*3.2.1.2.1. Crop production*

The analysis of the oilseed crop production in the study area involved the collection of information from local energy crop farmers (by questionnaires), experimental activities performed in the University farm and bibliographic research.

The energy crops more widespread and adapted to the pedological and climatic conditions of the territory are the rapeseed (*Brassica napus* L. var. *oleifera* D.C.), the sunflower (*Helianthus annuus* L.) and the soybean (*Glycine max* L.) (Santamaria *et al.*, 2007). These annual crops are characterized by different growth cycles: from the beginning of the spring to the end of the summer for sunflower and soybean, and from autumn to the spring for rapeseed. The crops do not have particular needs in terms of soil texture or nutritional requirements, though providing greater yields with irrigation (Santamaria *et al.*, 2007, Signor *et al.*, 2008). The climate of the plain area in NE Italy is Mediterranean with hot summers and rainfall concentrated in autumn (ARPA FVG, 2012). The study was performed for the areas defined suitable or highly suitable for above oil crops as reported in Santamaria *et al.*, 2007. On the basis of farmers interviews, local experimental results and related literature (Danielis *et al.*, 2005; Santamaria *et al.*, 2007; Signor *et al.*, 2008; Signor and Barbiani, 2009), Tab. 3.1 summarizes yields and agricultural techniques with high and low input level for the cultivation of rapeseed, sunflower and soybean representative of the widespread practices in study area.

Crop production analysis used Ecoinvent libraries which contain life cycle inventories for the inputs of this sub-system. The inventory data are related to the fuel production and consumption for farming and transportation, to the use and production of seeds and fertilisers, to the plant protection, the irrigation, to the use and depreciation of charge machinery, buildings and silos, and to the drying processes. The use of resources and the amount of emissions during the production, the maintenance and repair and the disposal of agricultural tillage machinery are taken into account.

*Assumptions*

In order to perform an objective comparison among the energy crops and different agricultural techniques, some factors have been set:

I) 10 km was considered as the average distance to cover with a tractor to store the harvest in the farm, and to transport seeds or pesticides until the farmer's cooperative.

II) Drying process was always considered even in cases where the seeds have the suitable level of moisture to be directly sent to the pressing process. The average distance between the farm and the dryer was considered equal to 15 km.

III) for the sizing of silos and loads to transport, a density of 0.77 t/m$^3$ for rape and soy seeds and of 0.62 t/m$^3$ for sunflower seeds has been considered.

*Emissions in agricultural phase*

Biomass use for energy generation could be potentially considered "carbon neutral" over its life cycle because combustion of biomass releases the same amount of $CO_2$ as was captured by the plant during its growth. By contrast, fossil fuels release $CO_2$ that has been locked up for millions of years (Ragauskas *et al.*, 2006, European Commission, 2009). However, GHG emissions, such as $CO_2$, $N_2O$ and $CH_4$, arising from bioenergy chain during crop growth, field management, feedstock processing and transport modify this equal balance and may reduce or completely counterbalance $CO_2$ savings of the substituted fossil fuels (Don *et al.*, 2012).

In order to meet a given demand of bioenergy a certain amount of feedstock is needed and, in general, these feedstock quantities can be obtained by (Gnansonou *et al.*, 2008): i) biomass use substitution (i.e. destined to bioenergy production instead of food and feed

Tab. 3.1. Inputs, outputs and yields inventory (per ha) for rapeseed, sunflower and soybean and two agricultural techniques with low and high input level (LI and HI respectively).

| | Unit | Rapeseed HI | Rapeseed LI | Sunflower HI | Sunflower LI | Soybean HI | Soybean LI |
|---|---|---|---|---|---|---|---|
| Input | | | | | | | |
| *Fertilisers:* | | | | | | | |
| N | kg N | 104 | 50 | 136 | 64 | 18 | 0 |
| P | kg $P_2O_5$ | 48 | 24 | 46 | 46 | 46 | 0 |
| K | kg $K_2O$ | 48 | 24 | 60 | 0 | 0 | 0 |
| Type | | NPK 8-24-24, Ammonium sulphate, Urea | NPK 8-24-24, Ammonium sulphate | Potassium chloride, Diammonium phosphate, Ammonium nitrate, Urea | Diammonium phosphate, Urea | Diammonium phosphate | |
| *Sowing:* | | | | | | | |
| Seeds | kg | 8 | 8 | 6 | 6 | 90 | 90 |
| *Pesticides:* | | | | | | | |
| Glyphosate | kg | 2 | 2 | - | - | - | - |
| Cypermetrin | kg | 0.1 | - | - | - | - | - |
| Metolachlor | kg | - | - | 2 | 2 | 2 | 2 |
| Fomesafen | kg | - | - | - | - | 0.5 | - |
| Bentazone | kg | - | - | - | - | 0.5 | - |
| *Operations:* | | | | | | | |
| Plowing | n. | 1 | - | 1 | - | 1 | - |
| Harrowing | n. | 1 heavy | 1 shallow | 1 shallow | 1 heavy | 1 shallow | 1 heavy |
| Sowing | n. | 1 september/october with fertilisation | 1 september/october wirh fertilisation | 1 march/april with fertilisation | 1 march/april with fertilisation. | 1 april/june with fertilisation | 1 april/may with fertilisation |
| Fertilisation | n. | 3 | 2 | 4 | 2 | 1 | - |
| Herbicide treatment | n. | 1 | 1 | 1 | 1 | 2 | 1 |
| Hoeing | n. | - | - | 2 | 1 | 1 | 1 |
| Insecticide treatment | n. | 1 | - | - | - | - | - |
| Harvest | n. | 1 june | 1 june | 1 september | 1 september | 1 september/ october | 1 september/ october |
| Irrigation: | | | | | | | |
| Number treatment | n. | - | - | 2 | - | 2 | - |
| Total water volume | $m^3$ | - | - | 600 | - | 600 | - |
| Output | | | | | | | |
| *Yield:* | | | | | | | |
| Amount | t | 3.6 | 2.9 | 3.9 | 2.9 | 4.5 | 3 |
| Humidity | | 12 | 12 | 12 | 12 | 13 | 13 |
| Essication | Yes/No | Yes | Yes | Yes | Yes | Yes | Yes |
| Yield at 9 % | t | 3,5 | 2,8 | 3,8 | 2,8 | 4,3 | 2.8 |

purposes), ii) crop area expansion, iii) shortening the rotation length and iv) yield increment in the same land.

The process of land use change (LUC) associated with introduction of energy crop production, can cause changes in the carbon stocks of soil and vegetation both directly in the areas where the change is occurred and indirectly in other areas (Fargione *et al.*, 2008; Searchinger *et al.*, 2008).

GHG emissions from indirect land use change are claimed to be even more important than emissions from direct land use change and, despite the high inaccuracy and calculation difficulties, some authors elaborated a range of values to show the magnitude of this effect (Di Lucia *et al.*, 2012). In this study the effects of LUC are almost null, given the spatial and time scale of the analysis (energy crops that supply a small/medium farm in the short term).

Due to agricultural production three relevant nitrogen emissions are released into the environment: ammonia ($NH_3$) and nitrous oxide ($N_2O$) as gas emissions and nitrate ($NO_3$) leaching into the ground water. Agriculture contributes considerably to the $NH_3$, $NO_3$ and $N_2O$ emissions. Especially for ammonia, agriculture is by far the main source of emissions (Brentrup and Küsters, 2000).

In detail has been used the following procedures to account each specific type of emission:

*Ammonia volatilisation*

Ammonia volatilisation occurs during and after production, storage and application of organic and mineral fertilisers. Volatilisation has been estimated according Brentrup and Küsters, 2000 and ECETOC, 1994, considering the type of the mineral fertiliser and peculiar weather conditions and soil properties of Italy (Tab. 3.2).

*Nitrous oxide emissions*

Nitrous oxide ($N_2O$) is one of the greenhouse gases and agriculture has a considerable

Tab. 3.2. Emission factors used for mineral fertilisers (% $NH_3$-N loss of total applied mineral N).

| *Mineral fertilizer* | *Emissions of $NH_3$-N per kg of N applied* |
|---|---|
| Ammonium nitrate, compound fertilisers | 2 % |
| Ammonium sulphate | 10 % |
| Urea | 15 % |
| Ammonium phosphate | 5 % |

share in anthropogenic $N_2O$ emissions. $N_2O$ is an intermediate product of the microbial processes of denitrification (conversion $NO_3^-$ to $N_2$) and nitrification (conversion $NH_4^+$ to $NO_3^-$) in the soil. The impacts of $N_2O$ emissions are especially significant for annual biofuel crops, since fertilisation rates are larger for these than for perennial energy crops. Crops grown in high rainfall environments or under flood irrigation have the highest $N_2O$ emissions, as denitrification is favoured under moist soil conditions where oxygen availability is low (Wrage *et al.*, 2005).

Almost the totality of the reviewed studies based on agricultural crops included estimations of $N_2O$ soil emissions in their assessments, and most of them show their relevant contributions to the final GHG balance (CONCAWE, 2006; Kim and Dale, 2008; Lettens *et al.*, 2003; Panichelli *et al.*, 2009; Reijnders and Huijbregts, 2008). These emissions are generally quantified as a fraction of fertilizer nitrogen content and are based on literature references such as IPCC default factors (IPCC, 2006). IPCC data estimate that about 1.0–1.5 % of N in synthetic fertilizer is emitted as N in $N_2O$ in temperate regions. A recent paper, which used a different procedure for estimating this emission, proposes a value of 3–5 % (Crutzen *et al.*, 2007). If this ‘‘extra” $N_2O$ emission is included in GHG balances of biomass systems, Crutzen *et al.* (2007) state that the global warming benefits of most first generation biofuels are completely annulled. As a consequence, this study is frequently cited as evidence against the use of biofuels as an effective means for mitigating climate change; by contrast, other studies claim that Crutzen *et al.* (2007) apply an uncertain approach, questionable assumptions and inappropriate, selective comparisons to reach their conclusions (North-Energy, 2008; RFA, 2008).

This paper uses the guidelines proposed in Crutzen *et al.*, 2007 to account $N_2O$ emissions in the atmosphere arising from the use of fertilisers and crop residues.

*Nitrogen oxide emissions*

Estimation of the nitrogen oxide ($NO_x$) emissions during denitrification processes in the soil was made according to Nemecek and Kägi, 2007 (eq.1):

eq.1 $$NO_x = 0.21 \times N_2O$$

*Nitrate leaching*

In order to estimate the amount of nitrogen leached ($NO_3$) from the energy crops during their agricultural cycle, a crop simulation model (*MiniCSS*, Rocca *et al.*, 2011) was applied. The simulation model is a set of relationships that formally describe the behavior of a system. These relationships are represented by mathematical formulas implemented in software (Leffelaar, 1993). A crop dynamic model, like *MiniCSS*, describes the system changes over the time as a function of the initial conditions, pedological and climatic features, crop morpho-physiological traits and agricultural technique. These models are important because allow an integrated evaluation of the effects of the weather, soil, species, cultivar and farm management on a very complex and dynamic system. *MiniCSS* has a modular structure. The module for soil dynamics carries out, with a mono-layer cascade approach, the simulation of soil water content considering maximum and actual evapotranspiration, runoff, infiltration, percolation and drainage into groundwater. The soil water reserve increases with rainfall and irrigation. Furthermore, it simulates the dynamics of soil organic matter with an implementation of the *RothC* model (Coleman and Jenkinson, 2008) and the nitrogen dynamics of soil, considering the fractions of nitrogen as nitrate and ammonium. The $NH_4^+$ concentration in the soil can increase due to the mineralization of organic matter or nitrogen fertilization.

In order to obtain a solid estimation of the average amount of nitrogen leached in suitable lands of North Eastern Italy 100 simulations have been done for each crop management type and for five stations distributed over the territory (Tab. 3.3). Each simulation was performed using different input meteo data generated with *Climak 3* (Rocca *et al.*, 2012) from historical series of the stations. This allowed a complete exploration of the climatic variability in the study area.

*$CO_2$ emissions from agrochemicals application*

The $CO_2$ emissions due to the use of agrochemicals is limited in our case studies to the urea application and estimated on the basis of an emission factor of 0.20 t of C/t of urea as suggested by IPCC (2006).

*Methane emissions*

Besides $CO_2$ and $N_2O$, the third most important GHG is $CH_4$. It is released in bioenergy process chain through combustion of fossil fuels, anaerobic decomposition of organic feedstocks and emissions from soil organic matter. In fact, cultivation of agricultural and lignocellulosic crops can reduce the oxidation of methane in aerobic soils, and thereby increase the concentration of methane in the atmosphere (Ojima *et al.*, 1993; Thustos *et al.*, 1998).The reduction in soil uptake (oxidation) of methane is related

Tab. 3.3. Leached nitrogen (kg N - $NO_3$ per t of Yield at 9 %) for each crop management types (three crops and two input level, low - LI - and high - HI -) and for five stations distributed on the study area. Results derive from 100 simulations with different yearly climatic parameter. Coordinates of the stations are referred to East Gauss Boaga projection, Roma 40 Datum.

| Station | Coordinates (E, N in m) | | Rapeseed HI | Rapeseed LI | Sunflower HI | Sunflower LI | Soybean HI | Soybean LI |
|---|---|---|---|---|---|---|---|---|
| Brugnera | 2329617.62 | 5087890.46 | 2.12 | 2.81 | 0.86 | 1.33 | 0.37 | 0.00 |
| Cervignano | 2390897.98 | 5078683.55 | 2.25 | 2.89 | 0.86 | 1.34 | 0.35 | 0.00 |
| Gradisca | 2402237.61 | 5082963.21 | 2.26 | 3.04 | 0.95 | 1.48 | 0.39 | 0.00 |
| San Vito | 2350508.39 | 5084780.84 | 2.10 | 2.74 | 0.98 | 1.55 | 0.37 | 0.00 |
| Talmasssons | 2376894.80 | 5082663.26 | 2.06 | 2.69 | 0.87 | 1.37 | 0.35 | 0.00 |
| Mean | | | 2.16 | 2.83 | 0.91 | 1.41 | 0.37 | 0.00 |

both to the use of nitrogen fertilizer and cultivation type; the reduction in methane uptake is equivalent to an emission of methane from cultivated soils. Such reduction is sensitive to a number of site-specific factors, such as soil temperature, soil moisture and the amount and kind of nitrogen fertilizer. As a consequence, measured effective emissions can range over orders of magnitude: $CH_4$ emissions related to fertilizer use can range from near zero to on the order of 100 g $CH_4$/kg N (Delucchi and Lipman, 2003).

However, Delucchi and Lipman noted that a value of 10 g $CH_4$ / kg N for $CH_4$ uptake reduction (which corresponds to a tantamount emission of $CH_4$) is reasonable for most circumstances and results in a relatively small contribution to life cycle GHG emissions of the bioenergy chain.

*Phosphates emissions*

Phosphates ($PO_4^{-3}$) emissions were estimated according to Rossier and Charles (1998) using an emission factor of 0.01 kg of $PO_4^{-3}$–P per kg of P applied as mineral fertilizer.

*Pesticide emissions*

The pesticides emission has been quantified according a worst case scenario criteria; considering the emission equal to the amount of pesticide applied (Ecoinvent, 2010).

*3.2.1.2.2. Oil production*

*Pressing and extraction*

The three crops considered have a different average content of oil in their seeds, respectively the 45%, 46% and 20% on dry matter for rapeseed, sunflower and soybean (experimental results).

The process to obtain oil from the seed is different according to its final use (production of SVO).The difference lies in the production scale. In small-scale SVO production, the seeds are processed in a screw press, with an oil extraction efficiency of approximately 70%, which leads to a higher content of oil in the cake meal than in the case of biodiesel.

The used screw press is suitable to extract crude vegetable oil from different kinds of oilseeds and able to process 200 kg of seed per hour (with different hourly production depending on the species and cultivar) using a continuous mechanical pressing. The oil is extracted between 25 and 75°C and the machine produces a protein by-product, in the form of pellet (piece diameter 8-10 mm, length 1-5 cm), directly usable as feed or fuel for heating. The pressing to obtain SVO, consumes only electrical energy, since simply a press and then some filters are used.

On the basis of experimental results and considering the available literature (Santamaria *et al.*, 2007), parameters regarding the oil production from rapeseed, sunflower and soybean reported in Tab. 3.4 have been obtained.

*Refining*

The crude oil obtained in the previously step is purified by a decanter and residues are sent to a second pressing. The purified oil undergo a refining process. The oil refining process involves several stages. In the SVO process, refining is done mainly to remove gums (water degumming process). Along with the gums this also decreases the phosphorus content, which is a critical parameter to meet the current standard of SVO as fuel DIN 51605 (2010).

Tab. 3.4. Oil production parameter for rapeseed, sunflower, soybean.

| *Parameter* | *Rapeseed* | *Sunflower* | *Soybean* |
|---|---|---|---|
| Oil in the seed on dry matter (%) | 45 | 46 | 20 |
| Oil extraction efficiency (%) | 75 | 75 | 65 |
| Processing capacity (kg/h) | 200 | 200 | 200 |
| Cake meal (% of the seed d.w.) | 69 | 68 | 88 |
| Oil (% of the seed d.w.) | 31 | 32 | 12 |
| Hourly cake meal production (kg/h) | 137 | 135 | 176 |
| Hourly oil production (kg/h) | 63 | 65 | 24 |

*Assumptions*

In order to obtain an objective comparison among the pressing processes of the three grain types, some factors has been fixed:

I) for the screw press: operating frequency 7200 h/year, life of 15 years, engine power 15 kW;

II) for the sizing of tanks, silos and loads to transport, densities of 0.64 $t/m^3$, 0.57 $t/m^3$ e 0.64 $t/m^3$ for the cake meals and of 0.920 $t/m^3$, 0.915 $t/m^3$ and 0.916 $t/m^3$ for the oil at 15°C respectively for rapeseed, sunflower and soybean, resulted from experimental analysis, have been assumed.

Ecoinvent data for oil production input regards machinery and building construction and electricity consume of screw press.

*3.2.1.2.3. Cogeneration*

The crude oil is burned in a CHP engine to produce electric power and heat. It uses an internal combustion engine with diesel cycle and power of 300 kWe. CHP technologies captures heat by-product produced during electricity generation in the form of vapor or other (e.g. diathermic oil by exchange system). The main problems associated to the low quality of the crude oil are a short engine lifetime (15,000 h) and high emission levels from combustion. For instance the concentration of NOx is higher than the limit reported in the Italian legislation (D.Lgs. 152/2006, P.V, All. I, P.3, 1.2). As far as the pollutant control is concerned, the cogeneration unit has a Selective Catalytic Reduction (SCR) system able to reduce of the 60-70 % emissions of nitrogen oxides ($NO_x$). SCR is a technology that injects urea - a liquid-reductant agent - through a catalyst into the exhaust stream of an engine. The urea sets off a chemical reaction that converts nitrogen oxides into nitrogen and water (Dones *et al.*, 2007). The cogenerator works with an operating frequency 6800 h/year and burns 0.230 kg of oil to produce a kWh.

*Emissions from cogenerator*

Emissions and engine lifetime were assumed on the basis of Ecoinvent inventory data. An engine fuelled by pure vegetable oil produces different emissions in respect to a diesel engine. In order to compare these technologies it has been assumed that the emissions of the first engine are poorer in CO (-13 %), hydrocarbon (-50 %) and particulate (-40 %) but present a $NO_x$ increase (14 %) (Winfried *et al*., 2008).

*3.2.1.2.4. Allocation procedures*

In order to compile a complete inventory of all the in- and outflows of the system, it is necessary to define rules for the allocation of the impacts. The largest part of the processes has more than one product or re-uses its intermediate products and wastes as its material sources. The material and energy flows must be allocated to the different products according to clearly defined procedures. In a process with different products (multifunctional), allocation can be done defining physical relationships among products (on the basis on their mass, volume) or of other type (economical value).

Energy allocation is the most accurate in this case, because the burdens of the process are shared among the by-products depending on its energetic use. To measure the energy of the vegetable oil, the lower heating value (LHV) is considered because this by-product will be used in a diesel engine. Cake meal energy content is estimated also using LHV.

The energy allocation procedure did not take into account the residues (straw) as recently idefined in EU Renewable Energy Directive (European Commission, 2009).

The allocation was based on:

I) Lower heating value (MJ/kg) for oil and cake meal obtained from experimental results (Tab. 3.5) and are similar to those reported by European Commission, 2009;

II) Efficiency for the CHP plant; 39 % and 43 % are respectively the electric and thermal efficiencies assumed.

*3.2.1.3. Life Cycle Impact Assessment*

Life Cycle Impact Assessment (LCIA) is the phase in which the sets of results of the inventory analysis is further processed and interpreted in terms of environmental impacts and societal preferences (Guinée *et al*., 2002). The evaluation has been performed in

Tab. 3.5. Allocation procedure adopted for products obtained by mechanical pressing.

| | *Products and by-products* | Rapeseed | Sunflower | Soybean |
|---|---|---|---|---|
| *LHV (MJ/kg)* | Oil | 37,6 | 37,7 | 36,8 |
| | Cake meal | 19 | 18,6 | 18,9 |
| *Energy allocation* | Oil | 47,1 % | 48,8 % | 26,6 % |
| | Cake meal | 52,9 % | 51,2 % | 73,4 % |

SimaPro v7.2.4 (PRé Consultant, Amersfoort, Netherlands) using three methods well documented and regularly used for the LCA studies: IPCC 2007 Global Warming Potential (GWP) 100 years (IPCC, 2007), Cumulative Energy Demand (CED, Frischknecht *et al.*, 2003) and CML 2 baseline 2000 (Guinée *et al.*, 2002). The first method quantifies gasses emissions on the basis of their potential effect on the global warming given a time horizon of 100 years (expressed in terms of kg of $CO_2$ eq).

Cumulative Energy Demand (CED) of a product represents the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials (Verein Deutscher Ingenieure, 1997). CED is expressed in MJ eq. CML 2 baseline 2000 is a method elaborated on SimaPro with the problem-oriented (midpoint) approach of CML 2001.

The LCIA consists of different sub-steps common to all the methods of analysis. Firstly, the inventory data are aggregated to effect scores using the equivalence factors and this is called classification/characterisation. The higher the equivalence factor, the higher is the contribution of an emission to the respective impact. After this mandatory step (ISO 14042, 1998), it could be performed some optional phases (normalization and weighting) in order to obtain further information on the studied phenomena. In this study normalization and weighting are excluded in order to avoid subjectivity in the analysis, and, in addition, there are no specific values available for the region under study (Iriate *et al.*, 2010).

The following impact categories were considered:

*Abiotic depletion potential (ADP)*: this indicator is related to extraction of minerals and fossil fuels due to inputs in the system (expressed as kg Sb eq);

*Acidification potential (AP)*: impact of acidifying substances released into ecosystems (kg $SO_2$ eq);

*Eutrophication potential (EP)*: impact of the losses of N and P to aquatic and terrestrial ecosystems (kg $PO_4$ eq);

*Global Warming Potential 100 years (GWP)*;

*Ozone layer depletion potential (OLDP)*: defines ozone depletion potential of different gasses (kg CFC-11 eq);

*Human toxicity potential (HTP)*: toxicity potential of each emission of a toxic substance to air, water and/or soil (kg 1,4-dichlorobenzene eq);

*Fresh water aquatic ecotoxicity potential (FAEP)*: toxicity potential for freshwater acquatic ecosystems (kg 1,4-dichlorobenzene eq);

*Marine aquatic ecotoxicity potential (MAEP):* toxicity potential for marine acquatic ecosystems (kg 1,4-dichlorobenzene eq);

*Terrestrial ecotoxicity potential (TEP)*: impact of toxic pollutants on terrestrial ecosystems kg 1,4-dichlorobenzene eq);

*Photochemical oxidation*: photochemical ozone creation potential (POCP) for each emission of Volatile Organic Compound (VOC) or CO to the air (kg ethylene eq).

Hectare-based impact (EI/ha) is useful to estimate the magnitude of impacts at different scale levels (regional, national, European) while energy based impact (EI/J) represents the environmental efficiency of a process. Therefore, EI/ha was used for estimate the net environmental gains, while EI/J to evaluate the efficiency. Moreover, land-based assessments allow to compare products with different purpose (e.g. food and energy crops) while the energy based impact are used for comparing only the energy crops (Fazio and Monti, 2011).

## 3.3. Results and Discussion

The EU Renewable Energy Directives' sustainability criteria stated that biofuels must offer at least 35 % GHG emission savings compared with fossil fuels, increasing to 60 % in 2018 (European Commission, 2009). The result discussion, organized in two parts, biomass vs biomass analysis and biomass vs fossil fuel and electricity mix analysis, will take into account these mandatory focuses.

*Biomass vs. biomass analysis*

Fig. 3.2 presents the global results of environmental impact assessment for rapeseed, sunflower and soybean cultivation considering the production per hectare. For each type of biomass, eleven impact indicators were calculated in six scenarios (combination of three crops for two different input levels). Fig. 3.3 shows the same type of comparison but using as functional unit the grain amount from which it is obtained 1 t of SVO. In every case (makes an exception fresh water aquatic eco-toxicity impact in Fig. 3.3) high level input cropping conditions produce greater impacts than the low input levels.

Considering the production per hectare, the sunflower cultivation has usually wider effects on environment than rapeseed and soybean and this is in relation with the amount of distributed fertiliser. Nonetheless, rapeseed high input cultivation often generates the highest emissions in terms of 1,4-dichlorobenzene eq. Fresh water aquatic ecotoxicity of rapeseed cultivation derives from the upstream processes, especially due to the production/distribution of pesticides (Cypermetrin) and complex fertilizer. Territorial ecotoxicity impact of rapeseed is instead related the emissions of seed production processes.

Changing perspective and taking into account oil yield, low input cropping system are again those with lower emissions but soybean becomes less profitable. Soybean cultivation provokes the worst impacts in terms of abiotic and ozone layer depletion, human and marine aquatic eco-toxicity, photochemical oxidation and has the highest energy demand. Sunflower remains the crop with the greatest input requirements in terms of fertilisers and generates the highest amount of $SO_2$ eq, $PO_4$ eq and $CO_2$ eq emissions.

Fig. 3.4 moves the focus on the energy content of the oil. Low input levels are, also in this case, the most advantageous. Soybean shows, on equal input level condition with other crop, the best environmental performances. Emissions values are in line with those reported in Fazio and Monti (2011) for rapeseed and sunflower in similar cropping conditions.

The results in Fig. 3.5 are given in total impacts per kWh produced electricity from biomass. Substantially, low input cropping system shows the lowest impacts. As in Fig. 3.2 the sunflower crop is the most impacting, following by rapeseed and sunflower; exceptions concern 1,4-dichlorobenzene eq emissions that are again the highest for rapeseed cultivation.

The results presented in Fig. 3.5 are aggregated overall the production chain and therefore more difficulty to see where the impacts originate. If these results are disaggregated over the main parts of the production chain (i.e. cultivation, oil production and cogeneration), it is possible to obtain more detailed information on how the emissions are distributed along the production chains of the three biomass types investigated here

In the case of global warming, the power plant has a small contribution to the overall release of GHG because it is assumed that the $CO_2$ emissions are compensated by the $CO_2$ absorbed during the growth of biomass. Crop production represents instead the principal source of $CO_2$ emission in the whole energy chain: from the 45 % of the total $CO_2$ emission generated with low input soybean cultivation to produce one kWh of power until the 85 % of the total $CO_2$ emissions derived from

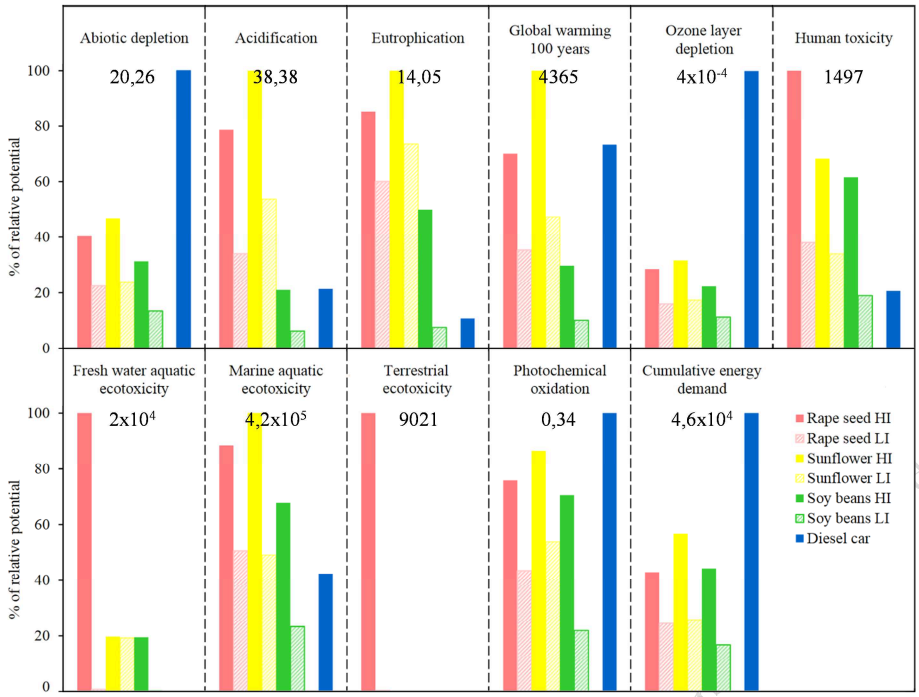


Fig. 3.2. Environmental impacts of the biomass production for six crop scenario (three crops with two input levels, low – LI – and high – HI -). The functional unit of comparison is the hectare. The impacts of a car that covers 15 km are shown to give an order of impact magnitude. The emissions were normalized on the highest value of the category. The values of reference scenarios are expressed in kg of substance equivalent for each impact category.

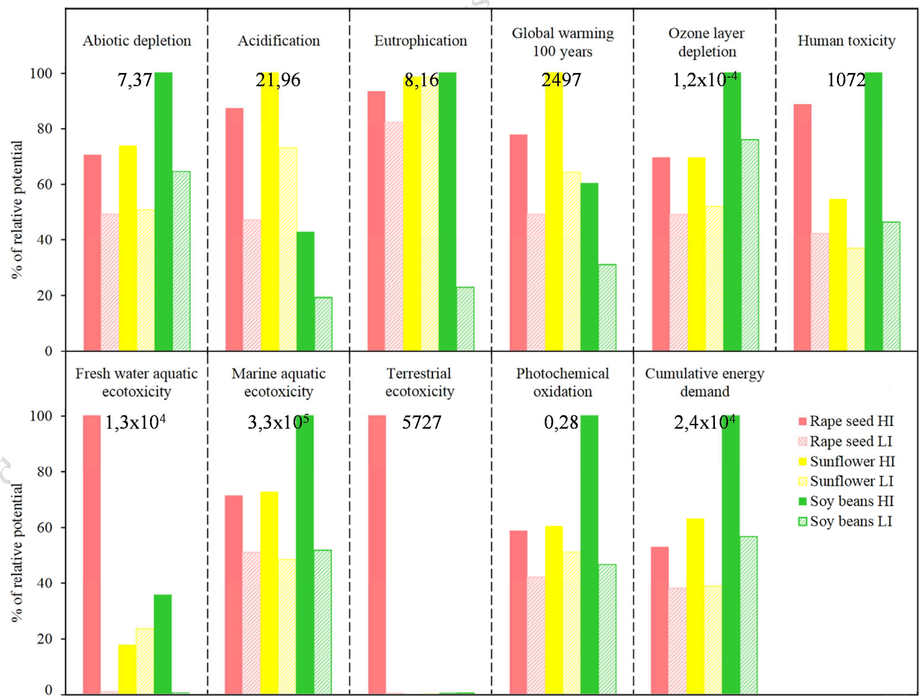


Fig. 3.3. Environmental impacts of the biomass production for six crop scenario (three crops with two input levels, low – LI – and high – HI -). The functional unit of comparison is the grain amount from which it is obtained 1 t of SVO. The emissions were normalized on the highest value of the category. The values of reference scenarios are expressed in kg of substance equivalent for each impact category.

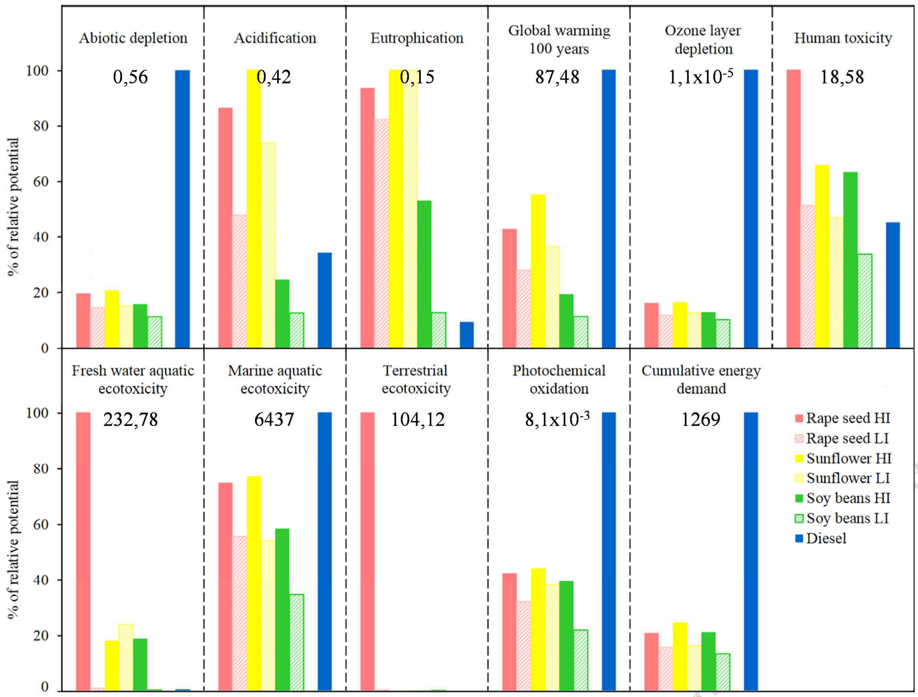


Fig. 3.4. Environmental impacts of SVO (three crops with two input levels, low – LI – and high – HI -) and diesel production considering 1 GJ of LHV as functional unit of comparison. The emissions were normalized on the highest value of the category. The values of reference scenarios are expressed in kg of substance equivalent for each impact category.

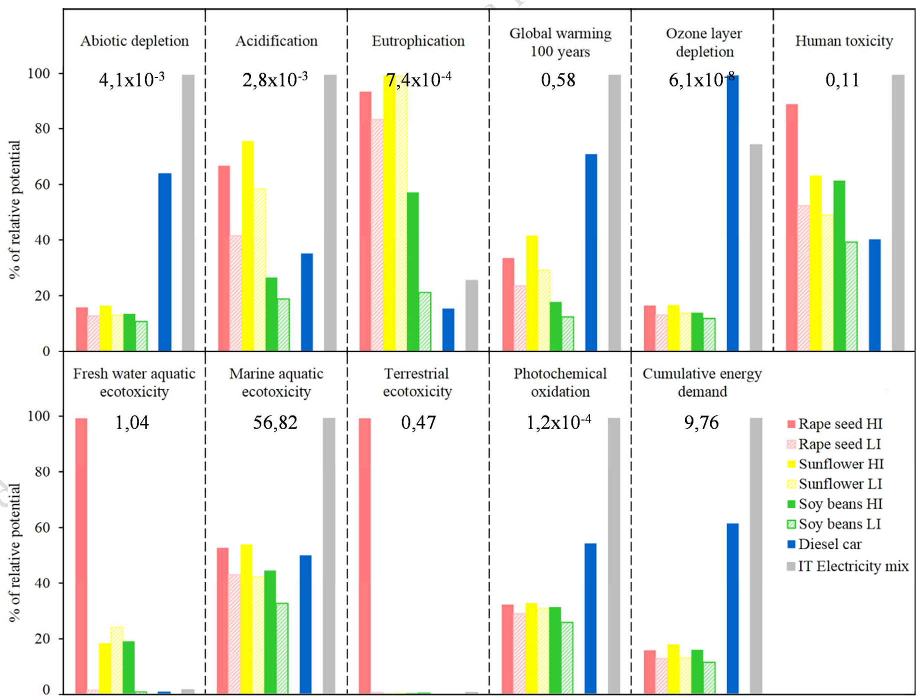


Fig. 3.5. Environmental impacts for the production of 1 kWh by cogeneration powered with SVO (three crops with two input levels, low – LI – and high – HI -), diesel and by the Italian electricity mix. The emissions were normalized on the highest value of the category. The values of reference scenarios are expressed in kg of substance equivalent for each impact category.

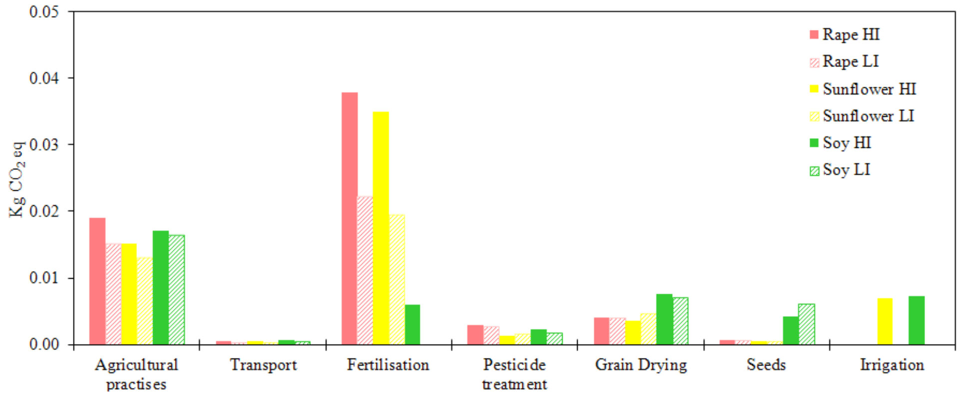


Fig. 3.6. Global warming potential of the crop production factors for six crop scenario (three crops with two input levels, low - LI - and high - HI -). The functional unit of comparison is the amount of biomass necessary to produce 1 kWh by cogeneration.

high input sunflower cultivation to produce the same power. Fig. 3.6 shows disaggregated data for crop production. As reported, the main contribution to global warming is due to the use of fertilizers in the field works. A possible measure for the reduction of these impacts would be the replacement of the mineral fertilizers with alternative natural fertilizers from agriculture or livestock waste.

*Biomass vs. fossil oil and Italian electricity mix*

Comparing SVO and diesel production corresponding to the energy content of a 1 GJ (Fig. 3.4), soybean oil production deriving from low input crop management allows to cut $CO_2$, Sb and CFC emissions by 90 %, $SO_2$ emission by 60 % and energy demand of about 85 %. Energy crops show worse impact than diesel production in terms of eutrophication, proportionally to the amount of fertiliser distributed during their cultivation.

It is interesting to compare the environmental profile of electricity from biomass with that of electricity from diesel and with electricity supplied to the Italian electrical network. Data related to diesel and Italian electricity mix are taken from Ecoinvent Database v.2.1, and are published respectively in 2003 and 2007.

Observe that the LCA of electricity from diesel and the Italian mix include the transport and distribution of electricity to the end users, meanwhile the LCA of electricity production from biomass does not include it.

Analysing Fig. 3.5, it can observe that the electricity from biomass, under the assumptions made in this study, has a worst environmental profile (more associated environmental impacts) than the diesel electricity for the categories Acidification (soybean excluded), Eutrophication, Human, Fresh water aquatic and Terrestrial eco-

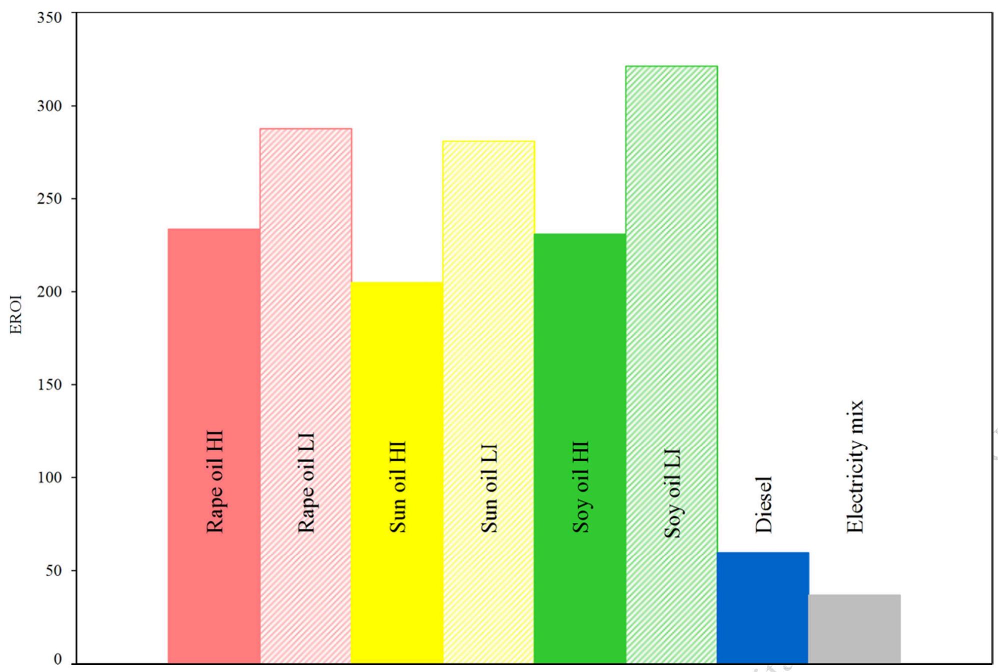


Fig. 3.7. EROI comparison for the production of 1kWh from SVOs (sunflower, rapeseed, soybean), diesel and Italian electricity mix.

toxicity, and for Marine Aquatic eco-toxicity with high input cultivation of rapeseed or sunflower.

Comparing electricity from biomass with electricity supplied at grid in the Italian network, we observe that electricity from biomass is "cleaner" for the most of the selected impact categories. There are exceptions for Eutrophication, Freshwater and Terrestrial ecotoxicity. This is due to the high dependence of the Italian electricity mix at grid on fossil fuels.

Acidification and eutrophication are strongly related to the fertilization: nitrogen volatilizes in form of ammonia and leached as nitrate, phosphorous directly increases nutrient content of soil. For these parameters, low input systems ensure the lowest impacts.

As far as energy demand is concerned, Fig. 3.7 shows Energy return on investment (EROI) for the production of 1 kWh from different biomass in comparison with diesel and electricity mix. The bests results corresponds to the low input cropping systems while energy demand for the production of electricity from diesel and from electricity mix don't counterbalance the gains.

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## List of Abbreviations

| | |
|---|---|
| *ADP* | Abiotic depletion potential |
| *AP* | Acidification potential |
| *CHP* | Combined Heat and Power |
| *EROI* | Energy Return On Investment |
| *EP* | Eutrophication potential |
| *FAEP* | Fresh water aquatic ecotoxicity potential |
| *GWP* | Global Warming Potential 100 years |
| *GHG* | Greenhouse gases |
| *HI* | High Input |
| *HTP* | Human toxicity potential |
| *LCA* | Life Cycle Assessment |
| *LI* | Low Input |
| *LHV* | Lower Heating Value |
| *LUC* | Land use change |
| *MAEP* | Marine aquatic ecotoxicity potential |
| *OLDP* | Ozone layer depletion potential |
| *POCP* | Photochemical ozone creation potential |
| *SVO* | Straight Vegetable Oil |
| *TEP* | Terrestrial ecotoxicity potential |

# 4

Evaluation of the medium/long energy chain (territorial level):

## Agro-energy supply chain planning: a procedure to evaluate economic, energy and environmental sustainability

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## 4.1. Abstract

The increasing demand for energy and expected shortage in the medium term, solicit innovative energy strategies to fulfill the increasing gap between demand-supply. For this purpose it is important to evaluate the potential supply of the energy crops and finding the areas of EU where it is most convenient. This paper proposes an agro-energy supply chain approach to planning the biofuel supply chain at a regional level. The proposed methodology is the result of an interdisciplinary team work and is aimed to evaluate the potential supply of land for the energy production and the efficiency of the processing plants considering simultaneously economic, energy and environmental targets. The crop simulation, on the basis of this approach, takes into account environmental and agricultural variables (soil, climate, crop, agronomic technique) that affect yields, energy and economic costs of the agricultural phase. The use of the Dijkstra's algorithm allows to minimize the biomass transport path from farm to collecting points and the processing plant, to reduce both the transport cost and the energy consumption. Finally, a global sustainability index (*ACSI*, Agro-energy Chain Sustainability Index) is computed combining economic, energy and environmental aspects to evaluate the sustainability of the Agro-energy supply chain (*AESC*) on the territory. The empirical part consists in a pilot study applied to the whole plain of Friuli Venezia Giulia (FVG) a region situated in the North-Eastern part of Italy covering about 161300 ha. The simulation has been applied to the maize cultivation using three different technologies (different levels of irrigation and nitrogen fertilization: low, medium and high input). The higher input technologies allow to achieve higher crop yields, but affect negatively both the economic and energy balances. Low input levels provides, on the average, the most favourable energy and economic balances. *ACSI* indicates that low inputs levels ensure a more widespread sustainability of the agro-energy chain in the region. High *ACSI* values for high input levels are observed only for areas with very high yields or near the processing plant.

**Keywords:** Biofuel, composite index, land evaluation, logistic optimization, modeling, simulation.

## 4.2. Introduction

The increasing demand for energy and expected shortage in the long term, solicit new energy strategies to fill the increasing demand-supply gap (EC, 2009; Tenerelli and Carver, 2012). European Commission intends to implement these strategies in a contest where the environmental and social goals are considered as well. A sustainable strategy must be addressed to achieve these three main goals: i) guarantee the security of the energy market; ii) minimize the environmental impact; iii) avoid the social consequences of energy shortage (UN, 1987). The biomass produced from the agriculture sector represents a potential renewable source of carbon-neutral material for the production of bioenergy (Ragauskas *et al*., 2006). The current debate on the sustainability of energy crops is focused on some controversial points: competition with food and fodder crops for fertile lands (Cassman & Liska, 2007), with other human activities for water resources (Service, 2009) and their effects on the direct and indirect land use change (Fargione *et al*., 2008; Searchinger *et al*., 2008; Di Lucia *et al*., 2012). Hence, it is important to evaluate the potential supply of the energy crops cultivated in some dedicated areas of the EU territory; this will require to evaluate the appropriate crops with the best energy performance (to maximize net energy yield), the environmental conditions to achieve the best performance of the land use (soil, fertility, water supply, climate, crop rotation …), the compatibility between food, fuel, social acceptance goal. The intensification of agriculture production could lead to severe consequences such as soil erosion and compaction, nutrient leaching, pesticide spreading and biodiversity loss. These considerations suggest to adopt the crop biomass production strategy, following an integrated agro-energy supply chain (*AESC*) approach that will solve simultaneously the economic, energy and environmental balances (Pimentel, 2003; WWI, 2006; Muller, 2008). This drives to a network approach that will integrate the activities of agents operating at different levels of the *AESC*: producers, processors and consumers, sequentially connected by the complementarity of the chain operations (Boehlje *et al*., 2003; Christopher, 2005; Rosa, 2008; Sexton *et al*., 2009). The *AESC* management requires to analyze the problems inherent production, processing, logistics (harvesting, transport and storage), marketing and channel diversifications, and the most efficient organization in order to coordinate the vertical integration and impose to the member the hierarchical decisions (Menard and Valceschini, 2005), in an environment characterized by the asymmetric distribution of information among partners and contingent risks caused by production and markets (Epperson and Estes, 1999). For this purposes, the spatial distribution of biomass and supply must be compatible with the demand and costs (production, processing, transport and distribution) (Grassano *et al.*, 2011; Tenerelli and Carver, 2012). This paper proposes an integrated and interdisciplinary approach to planning the biofuel supply chain at a regional level aimed to evaluate the potential use of the land for the energy production and side effects, to supply the existing processing plants and accomplish with the economic, energy and environmental targets. The problem of biomass allocation is dealt by integrating the territorial and climatic information in a crop simulation model (*MiniCSS*; Rocca and Danuso, 2011). The approach is based on the simulation of agricultural and environmental variables affecting crop yields, production technologies and related costs. Moreover, this methodology uses an optimized product flows from the farm to collecting points and processing plants and evaluate the risk caused by price volatility. At first, the dynamic crop simulation takes into account the climate variability; in later stages the results are used in a routine to optimize transports along the existing road network. Finally, the procedure produces for the whole biofuel chain a global suitability index. This index combines economic, energy and environmental results to evaluate the sustainability of bioenergy crops on the territory.

The purposes of this research are: 1) to analyze the effects of the interaction between pedo-climatic events, affecting the variability of crop yields and their energy balance; 2) to optimize the biomass hauling from field to collecting points and processing plants, with maximization of the return by assuming a cooperative organization; 3) to optimize the performance of the *AESC* by considering simultaneously the economic, energy and environmental balance.

## 4.3. Materials and methods

The agro-energy chain is composed by the rural territory, the collecting points, the processing plants and the roads connecting all these points. Biomass is produced in farm parcels, transported and stored in intermediate collecting centres and transformed in biofuel by processing plants. At first, the procedure requires the definition of the production system with pedo-climatic description. The choice of the crop and related agricultural technique is addressed to make a crop growth simulation in specific areas of the territory (Fig. 4.1). The analysis of the road graph detects the minimum paths between the parcels and the conversion plants, in order to optimize the biomass transport from

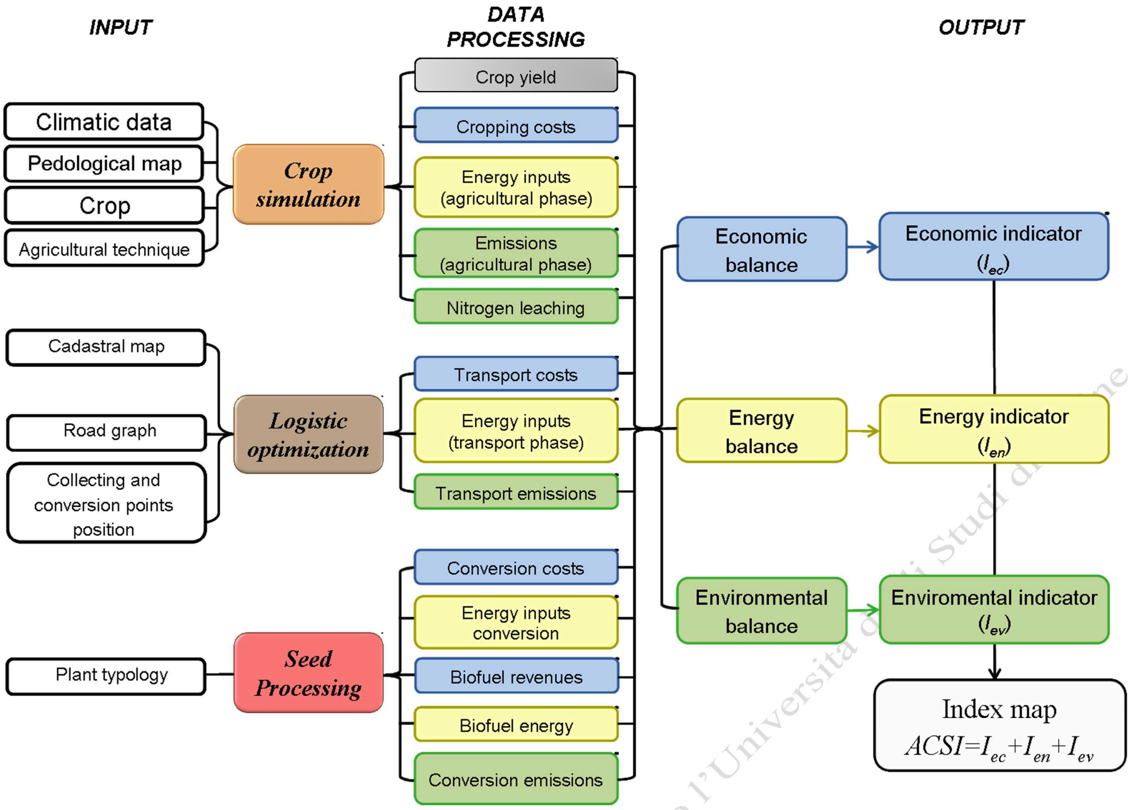


Fig. 4.1. Procedure framework (inputs, data processing and outputs).

farm to collecting points and to processing plant. In the conversion phase the economic value of biofuel and by-products and their costs are calculated; it is also estimated the energy balance. Finally the economic, energy and environmental balance of the *AESC* are calculated and used to elaborate a composite index of the crop sustainability of the territory (*ACSI*, Agro-energy Chain Sustainability Index, explained in detail later). This procedure takes into account five sources of variability: soil characteristics and availability, climate, road network, agricultural techniques and crop. The first three factors are site-specific for the territory and are a part of variability that is to be considered, but independent from the farmer choices. The latter two are variability sources directly controllable by agronomic choices and so are optimizable.

### 4.3.1. Study area

The procedure was applied to a study area represented by the whole plain of the Friuli Venezia Giulia (FVG) region, North-Eastern Italy (Fig. 4.2). It consists of about 295000 parcels of arable land, for a total area of about 161300 ha.

The spatial position of the parcels was defined using the geo-referenced database of the regional census of agricultural activities performed in 2009 with a map scale 1:2000

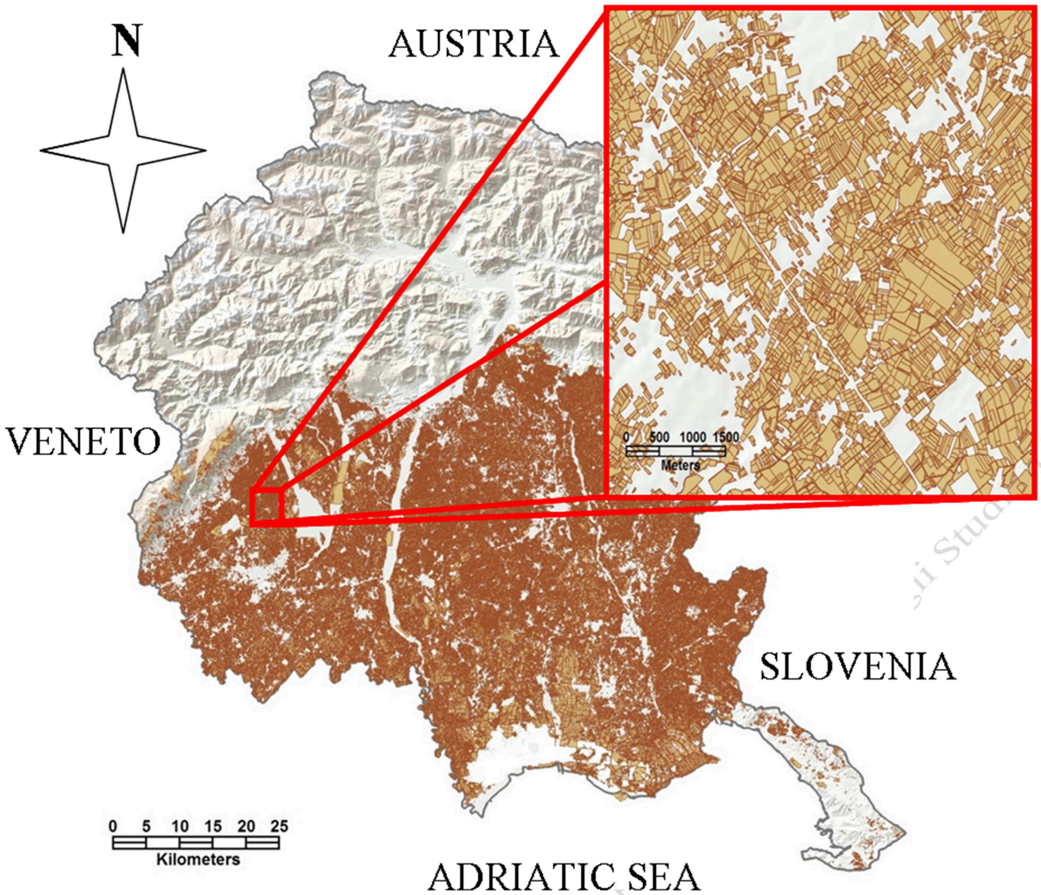


Fig. 4.2. Cadastral map of the study area.

provided from Friuli Venezia Giulia Region. The parcels were classified in 140 homogeneous classes, according to their pedological and climatic conditions.

The vectorial method has been used to represent all spatial information in this paper.

**4.3.2. Pedo-climatic classification**

Pedological and climatic conditions play an important role in agricultural activities, substantially determining crop yields. The soil classification was made considering texture, permeability, cation exchange capacity and the available water content (Fig. 4.3, on the left). These data were obtained from thematic maps provided by the Regional Agency for Rural Development (ERSA). Each map, in turn, classifies the specific variable into three classes. The combinations of these spatial information resulted in 22 soil types came out of the 81 potentially possible combinations (Tab. 4.1).

The meteorological data, for 17 meteo stations, were provided by OSMER FVG (OSservatorio MEteorologico Regionale). From these historical data and for each meteorological station, the climatic parameters for the weather generator *Climak 3* (Danuso, 2002; Rocca *et al.*, 2012a) were estimated and used to generate series of 100

Tab. 4.1. Soil types in the study area and their features, classified using the available soil traits.

| Soil Code | Number of Parcels | Total Area (ha) | Available water content | Cation exchange capacity | Texture | Permeability |
|---|---|---|---|---|---|---|
| S1 | 16018 | 5991 | *low* | *low* | *medium* | *high* |
| S2 | 15725 | 7597 | *low* | *low* | *coarse* | *medium* |
| S3 | 21018 | 10335 | *low* | *low* | *coarse* | *high* |
| S4 | 382 | 144 | *low* | *medium* | *medium* | *medium* |
| S5 | 45955 | 19441 | *low* | *medium* | *coarse* | *medium* |
| S6 | 3815 | 3850 | *low* | *medium* | *coarse* | *high* |
| S7 | 7137 | 4404 | *medium* | *low* | *medium* | *high* |
| S8 | 1978 | 1315 | *medium* | *low* | *coarse* | *high* |
| S9 | 810 | 888 | *medium* | *medium* | *medium* | *medium* |
| S10 | 45031 | 19341 | *medium* | *medium* | *coarse* | *medium* |
| S11 | 6836 | 3046 | *medium* | *medium* | *coarse* | *high* |
| S12 | 2561 | 1273 | *medium* | *high* | *fine* | *medium* |
| S13 | 16647 | 9575 | *medium* | *high* | *medium* | *medium* |
| S14 | 8048 | 3774 | *medium* | *high* | *coarse* | *medium* |
| S15 | 1565 | 498 | *medium* | *high* | *coarse* | *high* |
| S16 | 4828 | 2471 | *high* | *low* | *medium* | *high* |
| S17 | 22998 | 13365 | *high* | *medium* | *fine* | *medium* |
| S18 | 993 | 644 | *high* | *medium* | *medium* | *medium* |
| S19 | 9781 | 13485 | *high* | *high* | *fine* | *low* |
| S20 | 51819 | 31380 | *high* | *high* | *fine* | *medium* |
| S21 | 8426 | 4498 | *high* | *high* | *medium* | *medium* |
| S22 | 2808 | 3973 | *high* | *high* | *coarse* | *medium* |

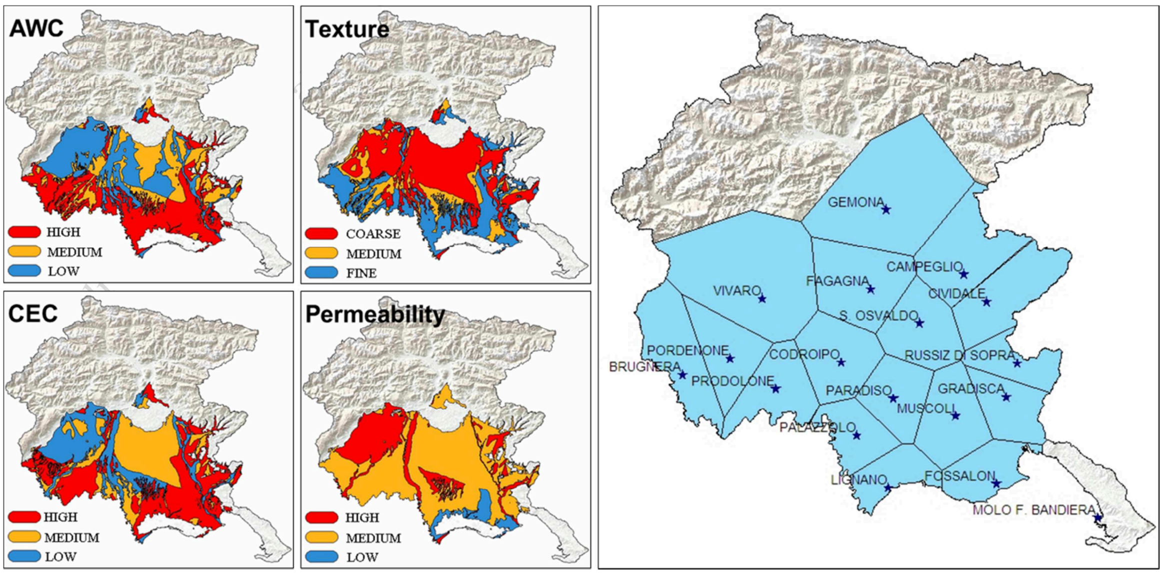


Fig. 4.3. Thematic maps of soil features (on the left): available water content (AWC), cation exchange capacity (CEC), texture and permeability. On the right, Voronoi spatialization of the meteorological series.

years. Generated meteo data were then spatialized using the Voronoi method, associating to each parcel the meteo data of the nearest station (Fig. 4.3, on the right). The historical and generated meteorological series consist of daily records of rainfall, solar radiation, minimum and maximum air temperature and reference evapotranspiration. Generated meteo series of 100 years allow to completely propagate the effect of climatic variability to the simulated crop production.

The combination between soil types (22) and climate conditions (17) produced 140 pedo-climatic typologies. A spatial query assigned to each parcel a specific soil-weather combination.

### 4.3.3. Crop simulation

Crop simulations, for each parcel, were performed using the model *MiniCSS*. This is a generic, daily step, dynamic crop simulation model, able to perform annual or multi-annual simulation. *MiniCSS* has a modular structure; each module represents a different part of the cropping system. The phenological and crop growth module simulates the development based on Growing Degree Days (GDD). This module also simulates biomass accumulation and crop yield using the radiation use efficiency approach. The model considers the reduction of the potential rate of growth due to the presence of stress conditions (non-optimal temperature, water shortage and lack of nitrogen). The module for soil dynamics carries out, with a mono-layer cascade approach, the simulation of soil water content considering maximum and actual evapotranspiration, runoff, infiltration, percolation and drainage into groundwater. The soil water reserve increases with rainfall and irrigation. Furthermore, it simulates the dynamics of soil organic matter with an implementation of the *RothC* model (Coleman and Jenkinson, 2008) and the nitrogen dynamics of soil, considering the fractions of nitrogen as nitrate and ammonium. The $NH^{4+}$ concentration in the soil can increase due to the mineralization of organic matter or to nitrogen fertilization. The management module generates the cropping practices (sowing, irrigation and fertilization) as events, using an internal decisional strategy. The economy module simulates the crop economic accounting, assuming all the inputs; capital (seed, fertilizer, pesticide, fuel and machinery) and labor are supplied in outsourcing, allowing to explicit all components of production cost. The energy module estimates the energy balance considering both direct and indirect energy inputs required for each agricultural practice. It uses an LCA (Life Cycle Assessment) approach (Brentrup *et al*., 2001; Brentrup *et al*., 2004) and the parameter for the energy accounting are derived from

Tab. 4.2. Agronomic treatments as considered in the maize crop simulations.

| | Input level | | |
|---|---|---|---|
| | *High* | *Medium* | *Low* |
| Tolerated water stress (% of easily available water)(1) | 20 | 50 | 80 |
| Total amount of N fertilization (kg ha$^{-1}$) | 300 | 175 | 75 |
| Number of N fertilizer application | 3 | 2 | 1 |

(1) A tolerated water stress of 50 % means that automatic irrigation starts only when the 50 % of the easily available water has been depleted. For example, in a soil type S1 (see Table 4.1) in the area of Codroipo, the seasonal amount of irrigation water applied, considering a water tolerated stress of the 50 %, is roughly 110 mm.

the Ecoinvent database 2.1 (Nemecek and Kägi, 2007). *MiniCSS* has been calibrated and validated for different energy crops and for the soil water and nitrogen dynamics (Rocca and Danuso, 2011; Rocca *et al.*, 2011b).

The simulation requires, as inputs, the following information:

- soil parameters and generated weather data derived from previous land classification;
- crop parameters: to test the procedure those of maize crop were chosen;
- agricultural technique: three input levels were imposed by modifying the maximum water stress tolerated by the crop and the level of nitrogen fertilization (Tab. 4.2).

One hundred simulations per parcel were performed, one for each year of the generated weather series. The model outputs taken into account were the mean of the crop yield (*CY*, t·ha$^{-1}$ of grain with 14 % moisture content), the agronomic costs (*AC*, €·ha$^{-1}$) and the energy inputs required in the agricultural phase (*AE*, GJ·ha$^{-1}$).

#### 4.3.4. Biomass transport optimization

The transport optimization problem is addressed to search for the shortest way to carry out the biomass from the field (each parcel of arable land on the territory) to the processing plant. It is important to underline that, due to the small sizes of the fields in the study area, it is strategically important to collect all the products in specific collecting points. This ensures reduced transport costs for the farmers and an increase of their bargaining power in the supply chain. Therefore, biomass transport includes two steps: the first one, from the field to the collecting point, is covered by using the farm trailer pulled by the tractor; the second step from the collecting point to the processing plant, is carried out with truck (assuming the weight more than 32 t). For this study, 53 collecting points (Fig. 4.4), already operative in the study area, were considered. Economic costs

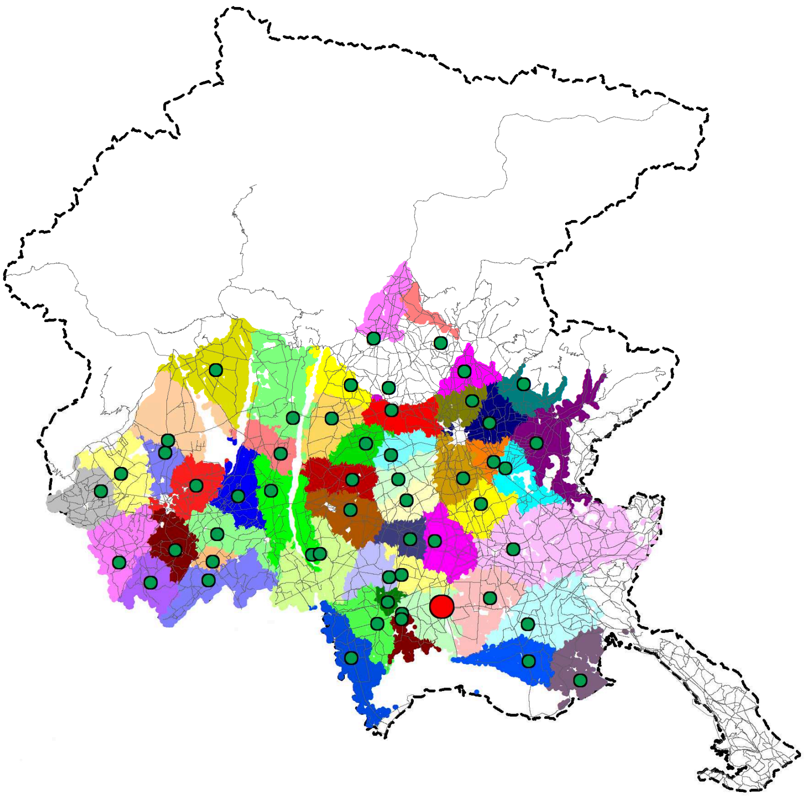

Fig. 4.4. Collecting points (small green circles), processing plant (big red circle), road network (grey continuous lines) and biomass collecting areas (colored areas) on the study area.

and energy input were calculated, separately, for both transport phases; their values were then referred per hectare for each single parcel.

The application of the Dijkstra's algorithm (Dijkstra, 1959) to the road graph (regional technical map of FVG - scale 1:5000) allows to minimize both the paths of the two transport steps (Fig. 4.4). The road graph has excluded the highways because their access is forbidden to the considered means of transport (e.g. tractor) or too expensive for the length of hauling. The transport costs (*TC*, €·ha$^{-1}$) were calculated according to the market prices and in relation to the road distance (km). The energy consumption during the transport phases (*TE*, GJ·ha$^{-1}$) was calculated using coefficients of energy consumption estimated by the software SimaPro v7.2.4 on the basis of Ecoinvent database 2.1 (Nemecek and Kägi, 2007).

### 4.3.5. Processing phase

For the purpose of the *AESC* it was considered the maize transformed into ethanol using a dry-mill plant and the DDGS (Dried Distillers Grains with Solubles) process. The biofuel yield (*BY*, L·ha$^{-1}$) obtained from a single parcel is determined from the crop yield

Tab. 4.3. Coefficients used to calculate revenues, costs, energy inputs and outputs of the maize processing phase.

| Coefficient | Unit | Value | Source |
|---|---|---|---|
| By-product value | €·L$^{-1}$ biofuel | 0.15 | Siemons *et al*., 2004 |
| Conversion costs | €·L$^{-1}$ biofuel | 0.28 | Siemons *et al*., 2004 |
| Energy content biofuel | MJ·L$^{-1}$ biofuel | 21.26 | Hill *et al*., 2006 |
| By-product credit | MJ·L$^{-1}$ biofuel | 4.31 | Hill *et al*., 2006 |
| Conversion energy | MJ·L$^{-1}$ biofuel | 12.73 | Hill *et al*., 2006 |

and calculated as:

$$BY = CY \times Kb$$

where *Kb* is the crop yield to biofuel conversion coefficient (398 L·t$^{-1}$).

Processing costs (*CC*, €·ha$^{-1}$) were calculated proportionally to the total biofuel production of the parcel, using the yield previously determined with simulation, and referred per hectare (see Tab. 4.3, according Siemons *et al*., 2004). The by-product value (*CopV*, €·ha$^{-1}$) was estimated assuming a profit from DDGS sale of 0.15 €·L$^{-1}$ of biofuel (Siemons *et al*., 2004) and referred to the hectare. The energy outputs from biomass processing include the fuel energy of the produced biofuel and the energy equivalent values for by-products that are typically used for aims different from energy commodities. The energy inputs are the energy costs of the conversion of crop to biofuel. The energy content of the produced biofuel (*BE*, GJ·ha$^{-1}$) was estimated using the coefficients proposed in the review of Hill *et al*. (2006) (Tab. 4.3). Other coefficients from the same paper were used to calculate the energy required to convert corn into biofuel and to assign by-product credits (*CopE*, GJ·ha$^{-1}$) as follows. For DDGS it was used an "economic displacement" concept using which it was calculated the energy required to generate the products for which DDGS serve as a substitute in the marketplace.

### 4.3.6. Agro-energy Chain Sustainability Index

The proposed index combines economic, energy and environmental aspects useful to determine the sustainability of bioenergy crop supply chain. The Agro-energy Chain Sustainability Index (*ACSI*) was defined as:

$$ACSI = w_{ec}I_{ec} + w_{en}I_{en} + w_{ev}I_{ev}$$

where:

$I_{ec}$ economic indicator (0-1)

$I_{en}$ energy indicator (0-1)

$I_{ev}$ environmental indicator (0-1)

$w_{ec}$, $w_{en}$, $w_{ev}$ are the weights of each indicator that take values between 0 and 1 and their sum is one. The assignment of the weights should be decided by decision makers, according to the goals they want to achieve or can be subjected to a negotiation among the stakeholders. There is also the opportunity of not considering some aspects of the proposed index giving a weight equal to zero to the corresponding indicator.

The values of the economic indicator ($I_{ec}$) were obtained from min-max normalization of the threshold prices ($TP$, €·L$^{-1}$), calculated for each parcel. Threshold price is the sale price of the biofuel (without taxes) that allows to balance chain costs and revenues:

$$TP = ChC / BY$$

where $ChC$ is the chain cost (€·ha$^{-1}$). All the elements that compose chain cost are explicated in the formula:

$$ChC = AC + TC + CC - CopV$$

Therefore $I_{ec}$ takes into account costs and revenues of the phases of production, transport and conversion of the biomass (revenues from the sale of biofuel). The normalization of the threshold prices considers, at the same time, the values for all the three agricultural techniques. It also takes into account the value direction assigning the minimum score to the larger values of the threshold price and the maximum score to the smallest one. Smallest thresholds are indeed indicative of greater suitability. Energy sustainability indicator Ien derives from the normalization of the energy chain balance ($EnB$, GJ·ha$^{-1}$) for each parcel. Also in this case, the normalization was obtained with min-max method considering jointly the values for the three agricultural techniques. In this case, greatest indicator values are associated to greatest values of energy balance which represent the more sustainable situations. Chain energy balance was defined as:

$$EnB = BE + CopE - AE - TE - CE$$

In the procedure it was attempted to represent the complexity of the agro-energy system as much as possible. However, at present, it does not consider environmental aspects (emissions) and Iev indicator is not calculated yet. Therefore, for economic and energy indicators the assigned weight was the same (0.5) in order to give them the same importance. To verify that indicators have the same influence on the composite index the $F$-test between their variances was performed (Nardo *et al.*, 2005).

## 4.4. Results and Discussion

The effects of the climatic variability on the production and consequently on the threshold price and on the energy chain balance are shown for three input levels in Fig. 4.5. The simulations were made on a single parcel with defined pedological and climatic features. Each curve represents the empirical cumulative distribution function of the values of 100 simulations for different annual climatic conditions.

The low input agricultural technique allows to obtain more favourable threshold prices and energy balances in comparison with other input levels. At the same threshold price, the low input curve shows the largest number of simulations (years) under this value. Assuming the final price of the biofuel without taxes equal to 0.70 €·L$^{-1}$, almost the 100 % of the low input simulations generate threshold price less lower than this value; with the medium input the value decreases to the 90 % and with high input technique below the 20 %. With the lowest input technique the cumulative function for energy balance gives the highest value.

The crop yields, threshold prices and energy chain balances for the study area are

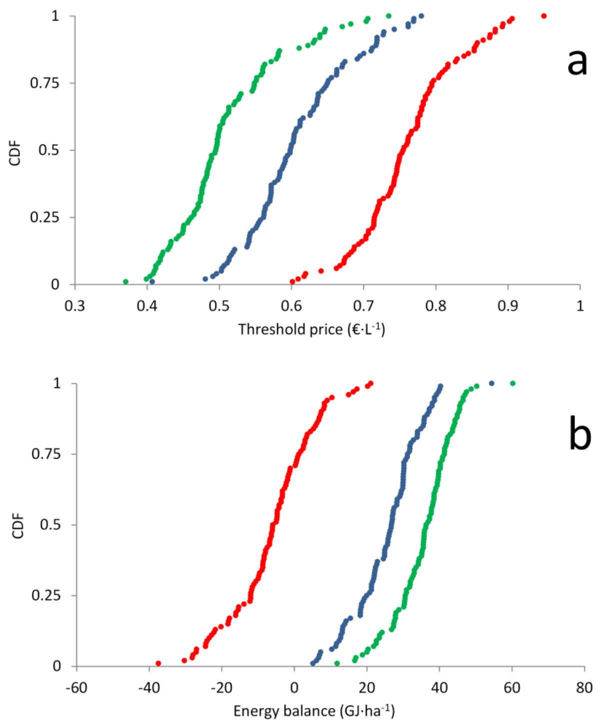


Fig. 4.5. Variability of the maize crop simulations in a single parcel with three input levels (high in red, medium in blue and low in green). Empirical cumulative distribution functions (CDF) are shown for the simulated threshold prices (a) and the energy chain balances (b). The crop simulations, for all the input levels, are performed using the same one hundred years generated weather series.

shown in Fig. 4.6. The statistics for the same variables and for the three agricultural theses are presented in Tab. 4.4. The high input levels ensure the maximum crop yields everywhere, but negatively influence the agronomic costs and, consequently, the threshold prices, making them less convenient. They also require the highest energy consumption leading to the lowest energy balance per hectare. The dispersion of the values of threshold price and energy balance extends increasing input level.

The spatial distributions of $I_{ec}$, $I_{en}$ and *ACSI* are shown in Fig. 4.7 and the relative statistics in Tab. 4.5. *F*-test between the indicator variances did not detect significant differences at 0.05 *p*-level so, they have the same influence on the composite index, assuming their equal weight. The indicators and the composite index take greater values for low input levels. The dispersion of the values of $I_{ec}$, $I_{en}$ and *ACSI* is larger for the highest levels of treatment. The total area in which indicators and the final sustainability index have more favourable values, close to one, increases progressively proceeding from high to low input. High *ACSI* values for high input levels are observed for areas with very high yields or near the processing plant. *ACSI* indicates that for the FVG region low inputs levels ensure widespread agro-energy chain sustainability.

## 4.5. Conclusions

The results of this pilot study in Friuli Venezia Giulia Region (FVG) suggest that the chain performance greatly depends on the biofuel final prices that affect the producer decisions to cultivate maize and this will determine the quantity of product that is related to scale economies in production, transport and processing.

Low input maize management techniques let to reach a widespread sustainability in all the FVG in economic and energy terms. High input levels gives their best results only in well-defined suitable land.

In this study maize, one of the most common energy crops, is considered. However, the procedure allows the comparison of alternative energy crops in a specific territory. In this sense, the future evolution of the procedure will be based on: 1) the comparison of the performance of different energy crops on the same territory; 2) the identification of the optimal use of the agricultural techniques to maximize the energy balances for each parcel (production problem); 3) the optimal distribution of the collecting points in the territory (logistic problem); 4) the optimal coordination among the agents operating at

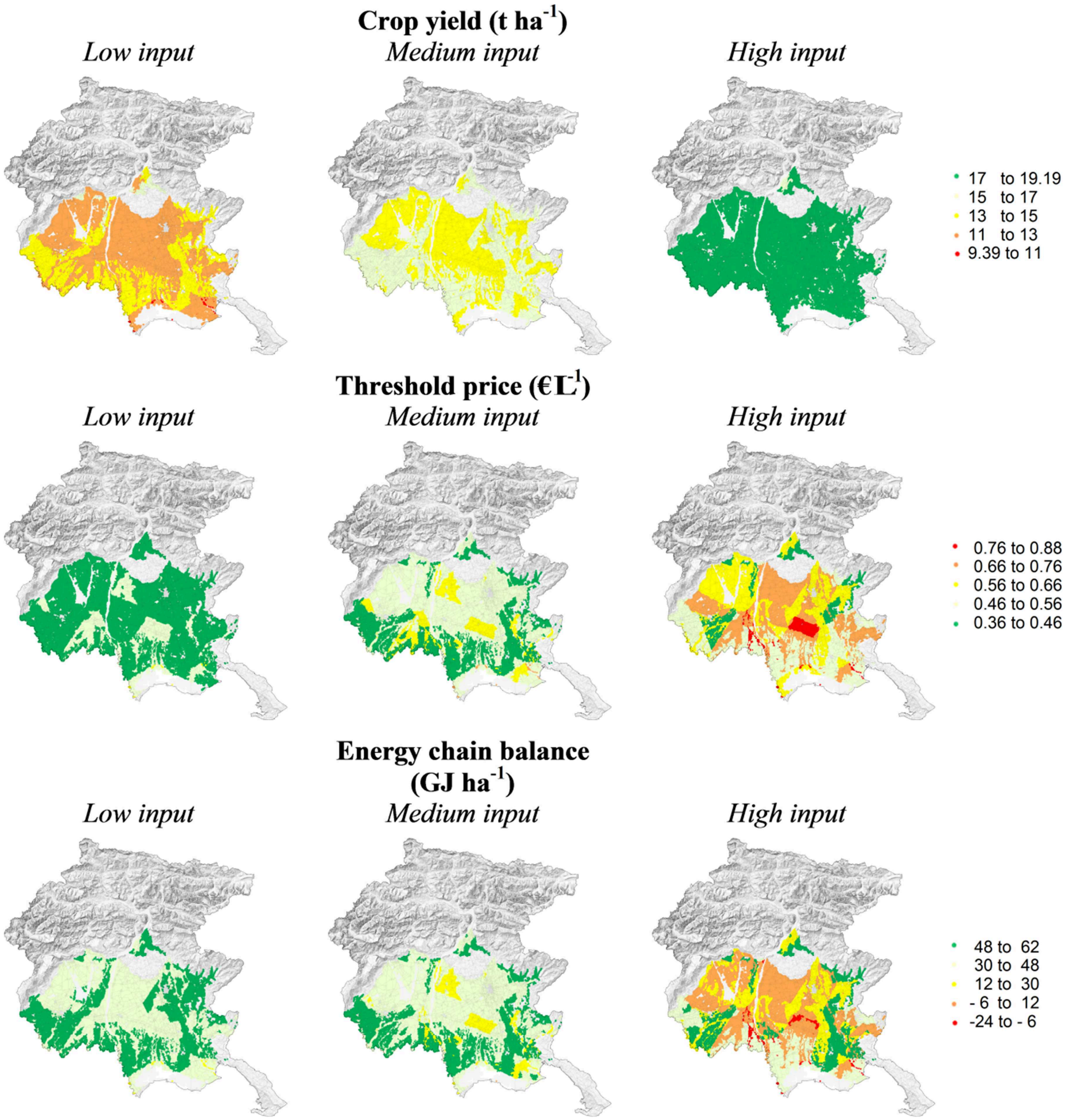


Fig. 4.6. Spatial distribution of the simulated maize yield, relative threshold price and energy chain balance.

Tab. 4.4. Results for the simulated maize yield, relative threshold price and energy chain balance for three input levels.

| | *Low input* | | | | *Medium input* | | | | *High input* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Min* | *Max* | *Mean* | *CV %* | *Min* | *Max* | *Mean* | *CV %* | *Min* | *Max* | *Mean* | *CV %* |
| Crop yield (t $ha^{-1}$) | 9.39 | 15.35 | 12.73 | 7.70 | 12.74 | 16.78 | 15.03 | 4.78 | 16.18 | 19.19 | 18.07 | 3.13 |
| Threshold price (€ $L^{-1}$) | 0.36 | 0.62 | 0.43 | 8.30 | 0.39 | 0.74 | 0.51 | 11.66 | 0.43 | 0.88 | 0.62 | 15.07 |
| Energy chain balance (GJ $ha^{-1}$) | 22.27 | 62.49 | 46.86 | 13.70 | 9.06 | 61.66 | 41.05 | 24.13 | -24.29 | 57.44 | 21.05 | 91.15 |

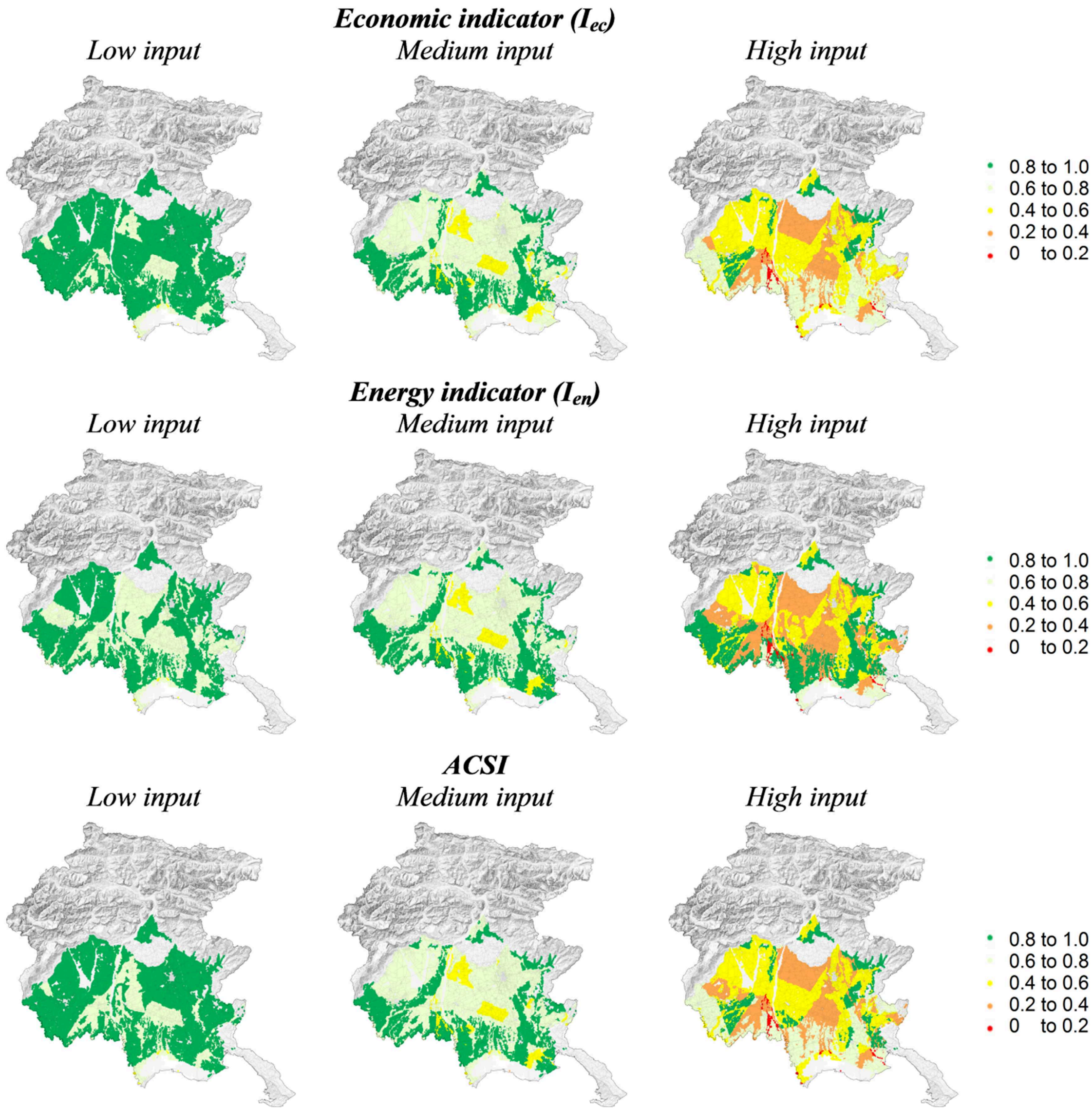


Fig. 4.7. Spatial distribution of the values of economic indicator ($I_{ec}$), energy indicator ($I_{en}$) and Agro-energy Chain Sustainability Index (*ACSI*) calculated for the maize crop. At present, *ACSI* does not include environmental indicator ($I_{ev}$).



different levels of the chain to improve the *AESC* performance (organization problem); 4) the reduction of the threshold prices and costs to expand the area of crop cultivation and supply for processing plants (efficiency of the *AESC* problem).

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Tab. 4.5. Statistics for the economic indicator ($I_{ec}$), for the energy indicator ($I_{en}$) and for the Agroenergy Chain Sustainability Index (*ACSI*) for three input levels of maize crop. Larger values indicate better suitability. The distribution of the study area within the indicator classes it is also reported.

*High input*

| | Indicator properties | | | | Total area for each indicator class (ha) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Min* | *Max* | *Mean* | *CV %* | *0-0.2* | *0.2-0.4* | *0.4-0.6* | *0.6-0.8* | *0.8-1* |
| $I_{ec}$ | 0.00 | 0.87 | 0.51 | 35.80 | 1379 | 40990 | 62282 | 45517 | 11120 |
| $I_{en}$ | 0.00 | 0.94 | 0.52 | 42.34 | 1766 | 56025 | 43994 | 13082 | 46421 |
| *ACSI* | 0.00 | 0.91 | 0.52 | 39.05 | 1379 | 44079 | 59193 | 42332 | 14305 |

*Medium input*

| | Indicator properties | | | | Total area for each indicator class (ha) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Min* | *Max* | *Mean* | *CV %* | *0-0.2* | *0.2-0.4* | *0.4-0.6* | *0.6-0.8* | *0.8-1* |
| $I_{ec}$ | 0.28 | 0.96 | 0.73 | 15.72 | 0 | 0 | 16460 | 92807 | 51767 |
| $I_{en}$ | 0.38 | 0.99 | 0.75 | 15.14 | 0 | 31 | 15540 | 88368 | 57349 |
| *ACSI* | 0.33 | 0.98 | 0.74 | 15.36 | 0 | 31 | 15650 | 89094 | 56512 |

*Low input*

| | Indicator properties | | | | Total area for each indicator class (ha) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Min* | *Max* | *Mean* | *CV %* | *0-0.2* | *0.2-0.4* | *0.4-0.6* | *0.6-0.8* | *0.8-1* |
| $I_{ec}$ | 0.50 | 1.00 | 0.88 | 8.01 | 0 | 0 | 258 | 28763 | 132266 |
| $I_{en}$ | 0.54 | 1.00 | 0.82 | 9.03 | 0 | 0 | 258 | 68731 | 92299 |
| *ACSI* | 0.52 | 1.00 | 0.85 | 8.45 | 0 | 0 | 258 | 41365 | 119665 |

cadastral data, the Regional meteorological centre - OSMER for meteorological data and the Regional Agency for Rural Development (ERSA) for pedological data.

## Notes

The presented procedure was implemented for raster maps with a SemGrid script (Danuso and Sandra, 2006) reported in Annex III and IV.

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## List of Abbreviations

*AC* Agricultural costs (€·ha$^{-1}$)

| | |
|---|---|
| *ACSI* | Agro-energy Chain Sustainability Index |
| *AE* | Energy inputs agricultural phase (GJ·ha$^{-1}$) |
| *AESC* | Agro-energy supply chain |
| *AWC* | Available Water Content |
| *BE* | Biofuel energy content (GJ·ha$^{-1}$) |
| *CC* | Conversion costs (€·ha$^{-1}$) |
| *Cdf* | Cumulative distribution functions |
| *CEC* | Cation Exchange Capacity |
| *ChC* | Chain cost (€·ha$^{-1}$) |
| *CopE* | By-product energy content (GJ·ha$^{-1}$) |
| *CopV* | By-product value (€·ha$^{-1}$) |
| *CY* | Crop yield with 14 % moisture content (t·ha$^{-1}$) |
| *DDGS* | Dried Distillers Grains with Solubles |
| *EnB* | Energy chain balance (GJ·ha$^{-1}$) |
| *FVG* | Friuli Venezia Giulia |
| *GDD* | Growing Degree Days |
| $I_{ec}$ | Economic indicator (0-1) |
| $I_{en}$ | Energy indicator (0-1) |
| $I_{ev}$ | Environmental indicator (0-1) |
| *Kb* | Crop yield to biofuel conversion coefficient (L·t$^{-1}$) |
| *LCA* | Life Cycle Assessment |
| *TC* | Transport costs (€·ha$^{-1}$) |
| *TE* | Transport energy consumption (GJ·ha$^{-1}$) |
| *TP* | Threshold price (€·L$^{-1}$) |
| $w_{ec}$ | Weight of economic indicator |
| $w_{en}$ | Weight of energy indicator |
| $w_{ev}$ | Weight of environmental indicator |

# 5

# *X-land*: a software for agro-energy land planning



**Article in preparation**

## 5.1. Aim

The aim of this work is to present a software application that uses an integrated and interdisciplinary approach to planning biofuel supply chain at the regional level considering soil productivity, climate, location with respect to collecting centres, processing plants and road network. The software is designed to evaluate the potential use of the land for energy production and its side effects, supplying the existing processing plants and accomplish with economic, energy, and environmental targets. Analysis considers different uncertainty and variability sources, such as climate and soil variability.

## 5.2. Materials and methods

The *X-land* application is formed by four components: 1) the crop simulation model engine *CSS* (Cropping System Simulator - Danuso *et al.*, 1999); 2) an executables' package that performs minimum path calculus among nodes of road network; 3) databases of crop, soil, agricultural operation, transport and processing parameters that can be selected or updated by the user; 4) the graphical user interface of the application (*X-land* itself).

The implementation methodology of *X-land* (Fig. 5.1) has been carried out by developing three different and parallel work plans: the simulation engine, the optimisation package and the user application.

The first one involved further development of the crop simulation model *CSS*, already tested and calibrated for some crops (Baldini *et al.*, 2010; Danuso *et al.*, 2010; Baldini *et al.*, 2011). *CSS* is a collection of interconnected modules that simulate the crop and soil dynamics and their interactions with the environment, i.e. crop phenology, crop biomass production, reduction of potential yield depending on water and nitrogen deficiency and soil dynamics of water, nitrogen, phosphorus, organic matter and crop residues. *CSS* works with a daily time step and requires input daily data of air mean temperature, water supply to the crop (precipitation and/or irrigation) and evapotranspiration. The model requires a parameter file containing soil and crop characteristics and an event file for setting up the management conditions.

The second task was the implementation of an executables' package for the logistic optimisation. The package associates both a collecting centre and a processing plant to each cell of the grid land use map, on the basis of the minimum distance criteria.

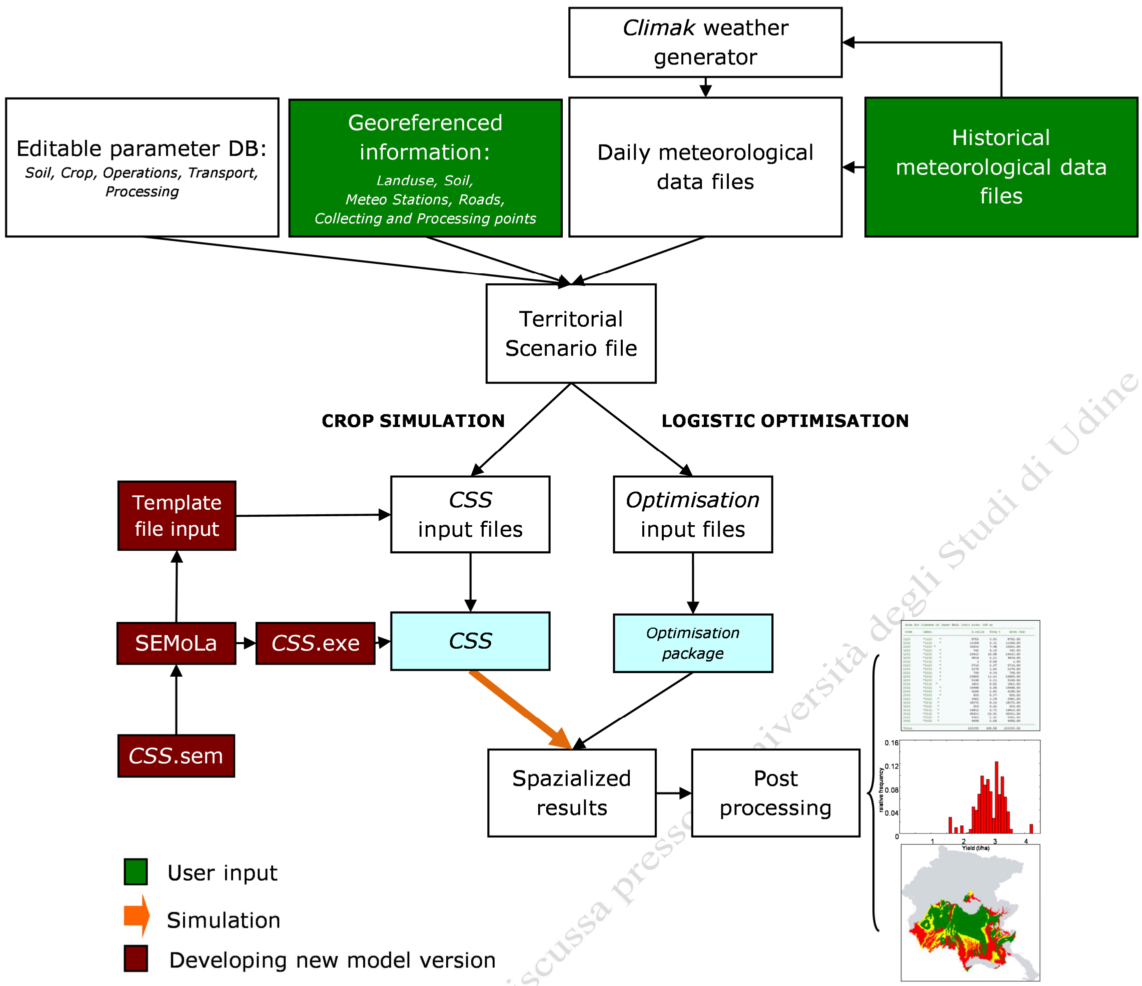


Fig. 5.1. *X-land* information flow and implementation methodology.

A collecting centre stores the harvests delivered from fields, whereas processing plant converts biomass in biofuel. The minimum distance corresponds to the length of the shortest path of all the paths between two points (cell to collecting point or collecting point to process plant) on the specific road network of the district.

The third task was the development of a simply to use graphical interface (*X-land*), that allows the user to set up the input data requested and to summarize the simulation results. Moreover, it allows the comparison of alternative scenarios.

The *CSS* model can use historical meteorological data or can generate synthetic meteo series by the *Climak* (Danuso, 2002) weather generator, already implemented in the installation package. Meteorological data can be checked or rebuilt by a specific procedure. *X-land* runs *CSS* and the optimisation package preparing to them the input files; after having the *CSS* simulation and minimum paths calculus completed, *X-land* reads and automatically post-processes the results of the executables.

This multi way implementation allows an easy and independent updating of the *CSS* model, without modifying the main functions of *X-land*, which remains with the same familiar graphical interface. Modular structure ensures also potential easy interchangability of the crop simulator.

### 5.2.1. Model overview

*CSS* has been developed using SEMoLa (Simple, Easy to use, Modelling Language; Danuso, 2003), a software framewok 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, based on states (stocks and flows) or on elements (like Individual Based Modelling) and discrete events. The ontology of the SEMoLa language originated from the System Dynamics approach, proposed by Forrester (1961) and widely used in describing continuous systems (Muetzelfeldt, 2003). A SEMoLa model is a text file, written with a declarative language, easy to understand and modify, that, after translation and compilation, becomes an executable file.

*CSS* has a modular structure (Fig. 5.2). Each module represents a different part of the cropping system. Besides the main module (*CSS*) connecting all the others, there are modules for phenology and crop growth (*CSS-CropYield*), soil dynamics (*CSS-SoilPhysics*), water balance (*CSS-SoilWater*), soil organic matter dynamics (*CSS-SoilRothC*), soil nitrogen (*CSS-SoilNitrogen*) and the cropping practices (*CSS-CropManag*). Furthermore, an economic budget module has been developed (*CSSmini_Economy*), that consider yield, market prices of products and operation costs, an energy module (*CSS-CropEnergy*) to account for crop energy balance, considering both direct and indirect energy inputs and an environmental module (*CSS-CropEnviron*) to quantify $CO_2$ and $NO_2$ emissions and leached nitrogen to the groundwater.

*CSS-CropYield* simulates crop phenology (growing phases depending on growing degree, days accumulation and day length), aerial and root biomass growth, crop yield and leaf area dynamics (based on the SUCROS model, van Laar *et al*., 1997). The aerial biomass (or crop biomass) is partitioned in leaves, stalks and storage organs. *CSS-CropYield* describes the growth from photosynthesis and respiration, and allocates the daily dry matter increments to the different organs according to the partitioning factors introduced as a function of the development stage of the crop.

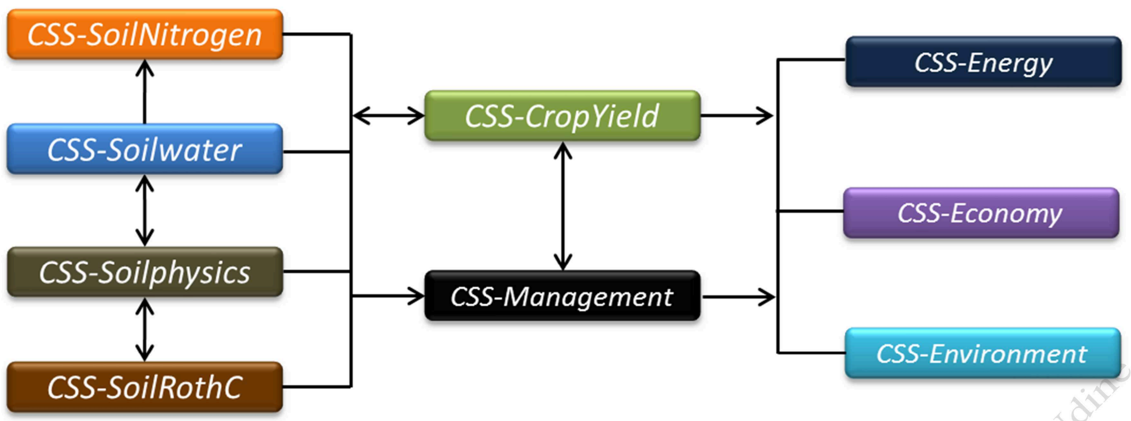


Fig. 5.2. *CSS* modular structure.

Soil is considered as divided into two layers: the upper layer or root layer and the lower or deep layer. The depth of the upper layer changes, according to the crop root growth, from the sowing depth to the maximum depth exploitable by the roots during the crop cycle. The soil layer between the rooting depth and maximum exploitable soil depth is the deep layer, maximum at crop sowing and decreasing as the crop roots continue growing. The maximum depth that can be reached by the root system depends on the crop characteristics, the presence of compact layers, gravel, rocks, or shallow water table. *CSS* simulates drainage to the water table and capillary rise from it, according to Driessen and Konijn (1992). If the depth of the phreatic water table bed is known, it also gives a simple simulation of the dynamics of water table depth.

Crop residue decay produces new humus and mineral compounds; they are divided into easily decomposable residues and those resistant to decomposition, with different mineralisation and humus synthesis coefficients. Soil microbial biomass is also considered. The balance of soil organic matter and residues is simulated, for the working layer, by an implementation of the *RothC* model (Coleman and Jenkinson, 2008).

The cropping techniques are considered as events; that is, as phenomena that happen and instantaneously modify parameters and states of the system. At present, the following events can be selected to build cropping scenarios: planting, organic and mineral fertilisation, irrigation, harvesting, pesticide treatment (only for economic and energy accounting), harrowing, hoeing, extirpation, chiselling and ploughing.

The economy module calculates the full costs of resources (variable and fixed costs) and revenues for crops. Economic information, obtained from market prices for agricultural activities (FRIMAT, 2008) is used as input parameters to the model. The economic information output is presented as data files to support decisions of investments and the analyses of the performance evaluation of the results obtained (Rosa, 2009).

The energy module computes both the crop energy and the direct and indirect energy used by their production. The Pimentel approach based on transformation coefficients has been used (Pimentel, 2003; Venturi and Venturi, 2003). The energy module uses an LCA (Life Cycle Assessment) approach (Brentrup *et al.*, 2001; Brentrup *et al.*, 2004) and the parameter for the energy accounting are derived from the Ecoinvent database 2.1 (Nemecek and Kägi, 2007). The information obtained by the energy modules can be used for balance purposes or to estimate the crop EROI (ratio between energy output and input).

The environment module accounts for the direct and indirect inputs and outputs between crop and environment ($NO_2$ and $CO_2$ emissions, N leached). Information to perform it is obtained from literature and simulated data (IPCC, 2006).

### 5.2.2. Logistic optimisation package

The agro-energy chain is composed by the rural territory, the collecting points, the processing plants and the roads connecting all these points. Biomass is produced in farm parcels, transported and stored in intermediate collecting centres and transformed into biofuel by processing plants.

The logistic optimisation package performs two sequential operations: the road graph building and the collecting areas definition. These operations require five input files with information on the study area: (i) vector file format (.dxf) of the road geometry; (ii) a text file (.csv) of their intersections; (iii) text files (.csv) of collecting and processing centres coordinates, and (iv) text file (.csv) containing centroids coordinates of the grid map cells.

*(i) Road graph building*

The graph theory has been used to represent the road graph and specifically: i) each road intersection represents a graph node; ii) each polyline segment between two adjoining nodes is an edge of the graph; iii) the road graph is a not-directed graph; iv) the edge weight is equal to its length.

The road geometry and the intersections are correlated because both the start and the end point of each road coincide with an intersection. The following relationship is valid:

$$(V_S \cap V_I) \neq \emptyset$$

where:

$V_S$ = set of nodes which compose the road polylines;

$V_I$ = set of intersections.

The package summarizes topological information of these two layers in a road graph. Generally, a graph $G$ is defined by two finite sets $V$ and $E$, where $V = \{v_1, ..., v_n\}$ is the set of $n$ nodes of $G$ and $E = \{e_1, ..., e_m\}$ is the set of $m$ edges of $G$. A couple of nodes of $G$, $e_k = (v_i, v_j) = e_{ij}$ , corresponds to an edge and the presence of an edge between them indicates a relation between them. Two nodes linked by an edge are called adjoining nodes. The graph is stored in an adjoining matrix $[a_{i,j}]$ defined in the following way:

$$a_{ij} = \begin{cases} 1 & if\,(v_i, v_j) \in E \\ 0 & otherwise \end{cases}$$

Given the $G$ weighted graph, it is possible to build the weighted adjoining matrix $[c_{i,j}]$, composed in the following way:

$$c_{ij} = \begin{cases} c(v_i, v_j) & if\,(v_i, v_j) \in E \\ 0 & otherwise \end{cases}$$

$[a_{i,j}]$ and $[c_{i,j}]$ are symmetrical matrix because the graph is not directed.

In order to avoid computational problem related to the dimension of the weighted adjoining matrix it is necessary to reduce the number of nodes and this requires the introduction of an exclusion criteria. The nodes are classified according to their position on the road polyline to filter those needless, thus defining polyline extremities and polyline middle nodes. A node could be simultaneously present in more polylines; for example could be the starting point of a road and the middle of another one. Moreover, the package assigns a degree to each node following the rules: i) each node has a starting degree equal to zero; ii) the degree is increased by one for each polyline where the node is an extremity; iii) increased by two for each polyline where it is a middle point. After degree calculations, the nodes resulting with a value equal to one are considered polyline extremities; those with a degree equal to two are considered middle points whereas those with an higher value are intersections. Middle points could be presented in the middle of a road polyline or connect two road polylines. They are not taken into account, unless they coincide with a collecting point or processing plant or if their removal creates ambiguity in adjoining matrix.

Finally, it is possible to build an optimised weighted adjoining matrix where each element $c_{ij}$ of the matrix represents the length of the edge $a_{ij}$ delimited by the nodes $i$ and $j$. In case there is no an edge from $i$ to $j$ (and consequently the symmetric $j$ to $i$) the element $a_{ij}$ in the matrix assumes value equal to 0 and if an element stays on the matrix diagonal it assumes value equal to infinite.

*(ii) Collecting areas definition*

A path in $G$ from $v_s$ to $v_f$ (arbitrary nodes) is a sorted set of nodes $c_{s,f} = \{v_s, v_{s+1}, \ldots, v_{f-1}, v_f\}$ with $(v_{i-1}, v_i) \in E \; \forall \; i=s+1, \ldots, f$. The weight of the path is defined as:

$$c_{s,f} = \sum_{e_i \in E_w} c_{i-1,i}$$

with $i = s+1, \ldots, f$;

where $E_w \subseteq E$ is a path composed by $i$ segments $e_i$ from $v_s$ to $v_f$. Given the set $W_{s,f}$ of all the paths from $v_s$ to $v_f$ in $G$, the aim of the procedure is to establish the path $w_{s,f}$ with the minimum cost. The cost in a road graph is linked to the travel time. It was assumed that the travel time is approximately proportional to the path length. In this way, the most favourable path from $v_s$ to $v_f$ in weighted graph $G$, where the weight of each arc is its length, is simply the shortest.

The implementation of the Dijkstra's algorithm (Dijkstra, 1959)[5.1] allowed to calculate the path from the centroid of each grid map cell (*CCen*) to the nearest collecting point (*CP*) and, in the same way, from each collecting point to the nearest processing plant (*PP*). It is a graph search algorithm that solves the single-source shortest path

[5.1] The algorithm works from a source $v_s$ by computing for each vertex $v_i$ pertaining to $V$ the cost $c(v_s,v_i)$ of the shortest path found so far between $v_s$ and $v_i$. Initially this value is set to 0 for the source vertex $v_s$ ($c(v_s,v_s)=0$), and infinity for all other vertices, representing the fact that it is not known any path leading to those vertices ($c(v_s,v_i)=\infty$ for every $v_i$ in $V$, except $v_s$). When the algorithm finishes, $c(v_s,v_i)$ should be the cost of the shortest path from $v_s$ to $v_i$ (or infinity, if no such path exists).

The basic operation of Dijkstra's algorithm rests on the essence of Dynamic Programming and is named edge relaxation. Let's suppose that it is looking the shortest path that goes from $v_s$ to $v_i$. If it is known the shortest path from $v_s$ to all possible $v_{i-1}$ connected to $v_i$ and if there are edges from those $v_{i-1}$ to $v_i$, then the shortest known path from $v_s$ to $v_i$ ($c(v_s,v_i)$) can be obtained through a path (the best path) from $v_s$ to $v_{i-1}$ by adding edge $(v_{i-1},v_i)$ at the end. This path will have length $c(v_s,v_{i-1})+c(v_{i-1},v_i)$. If this is less than the current $c(v_s,v_i)$, the current value of $c(v_s,v_i)$ with the new value can be replaced. Edge relaxation is applied until all values $c(v_s,v_i)$ represent the cost of the shortest path from $v_s$ to $v_i$. The algorithm is organized so that each edge $(v_{i-1},v_i)$ is relaxed only once, when $c(v_s,v_{i-1})$ has reached its final value.

The algorithm maintains two sets of vertices $S$ and $Q$. Set $S$ contains all vertices for which it is known that the value $c(v_s,v_i)$ is already the cost of the shortest path and set $Q$ contains all other vertices. Set $S$ starts empty, and in each step one node is moved from $Q$ to $S$. This vertex is chosen as the vertex with lowest value of $c(v_s,v_{s+1})$. When a vertex $v_{s+1}$ is moved to $S$, the algorithm relaxes every outgoing edge $(v_{s+1},v_{s+2})$.

problem for a graph with not-negative weighted edge, producing a shortest path tree.

The minimum path between two points (*CCen* to *CP*, or *CP* to *PP*) includes the projections' length of these points on the road graph. Each point projection has not been done on the nearest segment but on which that allowed to obtain the shortest path between starting and arrival point.

The collecting areas are constituted by all cells providing biomass to the same collecting centre.



### 5.2.3. Application description

*X-land* v1.0 (Fig. 5.3) is a software application with a graphical interface running under Windows OS. Its main purpose is to analyse the suitability of a district for the introduction of agro-energy chain considering farmer's income, energy and environmental chain balances.

The crop simulation engine (*CSS.exe*) can be easily modified, improved, rebuilt and tested using the SEMoLa framework (Fig. 5.1); calculation algorithms can be changed without the need to create a new graphical interface. This feature can be important for the on-line update of the model.

At present, *CSS* may perform annual or multi-annual simulations but not for crop rotation. By screen choices the user can create the "land scenario", which contains all the needed information for the calculation procedures.

#### 5.2.3.1. The land scenario

The scenario is a text file that sets up the agro-energy chain analysis: the program, by interacting directly with the screen choices, meteorological data, parameter databases, automatically generates a simulation file (*simfile*) that specifies the simulation type. In this way it is possible to create different complex simulations combining territorial layer, meteorological data, crop parameter and agricultural practices.

The scenario file is created by integrating two types of information: territorial data and management choices. The software requires the following territorial layers:

*i)* Grid map of land use classes on which perform agro-energy chain analysis. Grid maps can be imported in different GIS file format (ArcGis, Idrisi, Surfer, Geomedia or Grass);

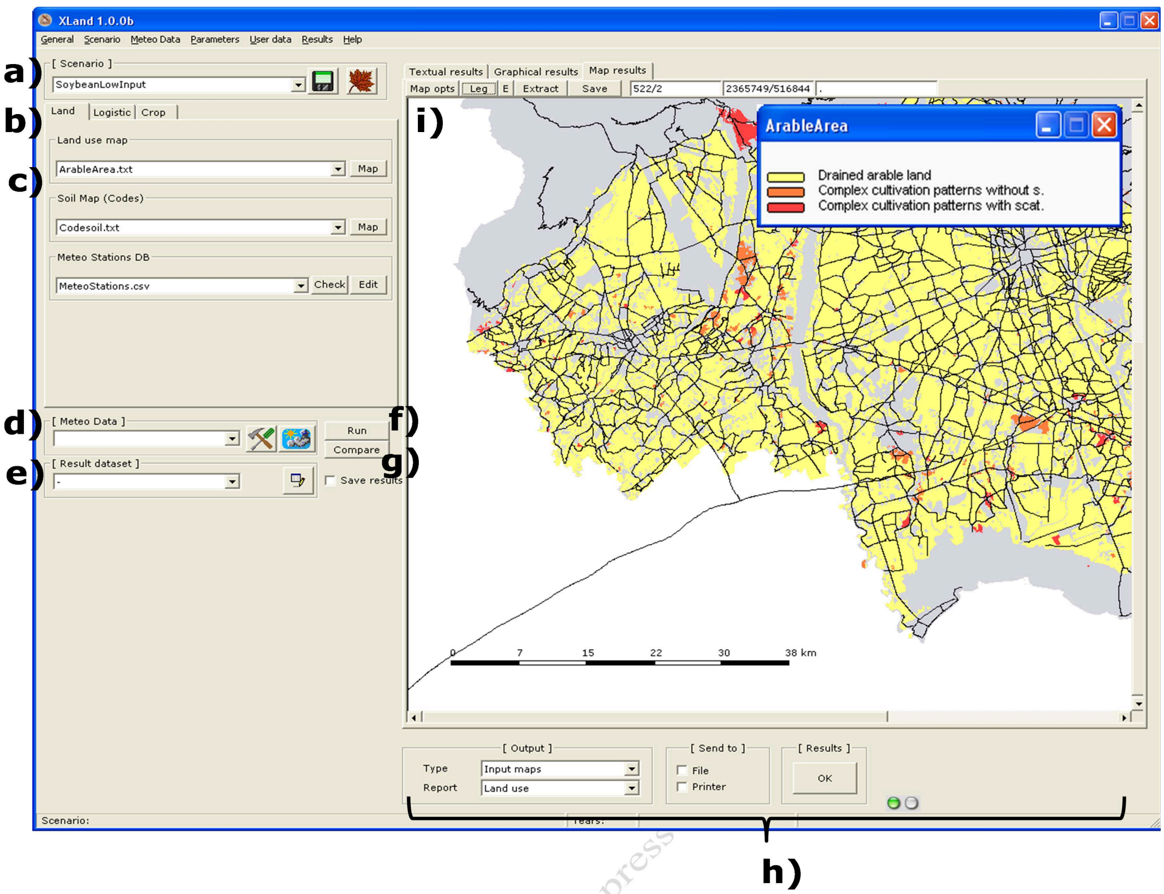


Fig. 5.3. The *X-land* application: a) sets, saves and deletes land scenario files; b) selects the type of information to set (land, logistic network or crop management); c) loads land use and soil maps, locates meteorological stations and loads meteo files; d) sets, loads, edits, fixes and generates the meteorological data file; e) loads simulation results; f) run simulation; g) run scenarios comparison; h) defines how to display results (text, graphic or map); i) result windows (text, graphic or map format).

*ii)* Soil types grid map. This layer classifies soils in classes, identified with a specific integer code, on the basis of soil parameter. A soil parameter dataset, in the soil parameter database described in detail below, has to correspond to each soil code;

*iii)* Meteorological stations file. This file contains the code and the coordinates for meteorological stations on the territory (.csv format). A meteorological daily data series is required for each station existing in the file and has to contain mean temperature (°C), rainfall (mm), solar radiation (MJ·m$^{-2}$) and reference evapotranspiration (mm). A meteorological data file can have one or more years of data; the number of dataset in the meteo file determines the number of simulations to be run. In this way the program will set up, automatically, a simple or a multi-annual simulation. Meteorological data can be prepared by the user in different formats: SEMoLa database dctfile (dct), Dbase (dbf) or comma separated value (csv). The last two, can be directly created also from a spreadsheet application.

*X-land* has many options for the check and the rebuilding of data in meteorological files: it assists the user in the creation of correct meteorological data file by automatic correction of the names of variables, changes the date format, and rebuild missing data. It also advises when the file is not correct for missing days, wrong time order and data out of range;

*iv)* Road geometry vector file (.dxf format) containing the selected road network for the biomass transport;

*v)* Road junctions coordinates text file (.csv format);

*vi)* Collecting and processing centres coordinates file (.csv format).

The procedure of minimum path definition takes into account the presence of natural obstacles (f.i. rivers) that increase the path length between two points.

Moreover, the user has to set the following chain management choices:

*i)* Crop management type: the user selects the crop and creates the scheduling of agricultural practices choosing the date, the operational method and, if necessary, the amount of the product to distribute. The available practises are: sowing, planting, irrigation, fertilisation, hoeing, chiselling, harrowing, extirpation, pesticides treatment, chopping and harvest;

*ii)* Transport method: select the vehicle to be used to transport biomass from field to the collecting centres and from here to the processing plant;

*iii)* Conversion method: pick the available conversion plant technology (dry mill or wet mill plant).

After territorial layers defining and the selection of crop, transport vehicles and conversion method, the related parameters, not directly displayed on the main window of the application, can be defined. It is possible to use default dataset or edit them to create custom parameter sets. Available editable database are:

*i)* Crop parameter database; selecting on screen a crop (maize, soybean, sunflower, wheat, etc.) all the related crop parameters are set. Working directly on database is possible to create custom sets of crop parameter for new crops or for specific uses (for example, to modify crop parameters for existing crop, after calibration);

*ii)* Soil parameter database; the software supplies some standard soil datasets, but it is easy to create other ones. In order to perform the crop simulation, soil parameter has to contain datasets for all the soil types loaded with the soil grid map;

*iii)* Cropping practise databases: there are some background dataset for each operation, relative to different operation typologies;

*iv)* Transport parameter database: consumption and emission parameter of the vehicles are estimated with software *SimaPro* v7.2.4 on the basis of Ecoinvent database 2.1 (Nemecek and Kägi, 2007). The default transport costs reflect currently market prices and are defined in relation to the distance (km) to cover;

*v)* Conversion parameter database: they differ depending on crop and technology and derive from literature (Hill *et al.*, 2006, Siemons *et al.*, 2004).

The manual setting of management choices and the editing of parameter database can be useful to perform alternative scenario analyses, in order to verify the behaviour of crops with real or hypothetical scenarios, or even with just the natural contributions.

#### 5.2.3.2. Agro-energy chain analysis

Having a study area corresponding to the cells of the grid land use map, at first the procedure defines homogenous areas for pedological and climatic conditions (PA) (Gustafson, 1998). Each area is characterized by specific soil properties and climate, arising from its particular soil type and reference meterological conditions. The latter are defined by a Voronoi spazialisation based on the meteo station coordinates.

Crop model performs simulations for the resulting PA using as input the corresponding meteo series and soil parameter dataset. The model runs for every combination a number of simulations equal to the length (years) of the shortest available meteo series. In this way simulations are independent from each other and it is possible to evaluate the climatic risk. Six crop simulation variables are accounted and their mean for PA is spatialised: dry yield ($t \cdot ha^{-1}$), agricultural costs (*AC*, $€ \cdot ha^{-1}$) and energy inputs (*AE*, $GJ \cdot ha^{-1}$), $CO_2$ crop balance ($t\ CO_2eq \cdot ha^{-1}$), leached nitrogen as $NH_4^+$ or $NO_3^-$ ($kgN \cdot ha^{-1}$).

The transport optimization problem is addressed to search for the shortest way to carry out the biomass from the field (each cell of land use map) to the processing plant. It is important to underline that, due to the small sizes of the fields in the some study areas, it is strategically important to collect all the products in specific intermediate collecting points. This ensures reduced transport costs for the farmers and an increase of their bargaining power in the supply chain. Therefore, biomass transport includes two steps: the first one, from the field to the collecting centre and the second from collecting centre to the processing plant. The application of the Dijkstra's algorithm to the road graph allows to minimize both the paths of the two transport steps and to define collecting areas.

Given the cell yields and their minimum distance to collecting and processing centres, the transport costs (*TC*, €·ha$^{-1}$), transport energy consumption (*TE*, GJ·ha$^{-1}$) and emissions (*TEm*, $tCO_2eq$·ha$^{-1}$) are calculated using the specific parameters contained in transport database for the chosen vehicles.

Biofuel yield (*BY*, L·ha$^{-1}$), its energy content (*BE*, GJ·ha$^{-1}$), conversion costs (*CC*, €·ha$^{-1}$) and energy consumption (*CE*, GJ·ha$^{-1}$) are derived from crop yield considering the plant parameters of the available technology.

The procedure takes also into account by-product value (*CopV*, €·ha$^{-1}$) and their energy content (*CopE*, GJ·ha$^{-1}$) calculated proportionally to the crop production (Hill *et al*., 2006, Siemons *et al*., 2004).

Finally, the analysis proposes two different indicator of land suitability for agro-energy production:

i) *Threshold price* (*TP*, €·L$^{-1}$) is the sale price of the biofuel (without taxes) that allows to balance chain costs and revenues:

$$TP = ChC / BY$$

where *ChC* is the chain cost (€·ha$^{-1}$). All the elements that compose chain cost are explicated in the formula:

$$ChC = AC + TC + CC - CopV$$

ii) *Energy return on investment* (*EROI*) is the ratio between usable acquired and expended energy along the three chain sub-systems: crop production, transportation and conversion process. *EROI* evaluates the chain efficiency and is defined as:

$$EROI = (BE + CopE)/(AE - TE - CE) \times 100$$

## 5.3. Results

### 5.3.1. The software result

After simulation, *X-land* generates a file containing many simulated variables (crop yield, agricultural $CO_2$ emissions, threshold price, energy balance and ratio, …) for each cell of the land use grid map.

Results can be shown in graphical, textual or map form, saved to a file or printed.

Categorical variables are represented as categorical maps and summarized in frequency tables and histograms instead continuous variables are plotted as float maps and synthetize with frequency tables and the calculation of layer statistics.

### 5.3.2. Case study

*X-land* was applied to a study area represented by the whole plain of the Friuli Venezia Giulia (FVG) region, North-Eastern Italy (Fig. 5.4). It consists of 222353 hectares of arable land derived from rasterisation (cell size 100 x 100 m) of the Moland map (JRC, 2002).

The soil classification and parameterisation was done considering texture, permeability, cation exchange capacity and the available water content. These data were obtained from thematic maps provided by the Regional Agency for Rural Development (ERSA).

The meteorological data, for 17 meteo stations (Tab. 5.1), were provided by OSMER FVG (OSservatorio MEteorologico Regionale). From these historical data and for each meteorological station, the climatic parameters for the weather generator *Climak 3* (Danuso, 2002; Rocca *et al.*, 2012) were estimated and used to generate series of 100 years.

The logistic network excluded highways and considers 53 collecting centres and a processing plant already operative (Fig. 5.4). Collecting areas defined by minimum path calculation on the road graph are shown in Fig. 5.5.

Transport and conversion parameter used in analysis are shown in Tab. 5.2.

The case study analyses soybean cultivation with two different crop management: low and high input level (Tab. 5.3, the same reported in Chapter 3). Soybean is one of the

Tab. 5.1. Meteorological station coordinates in m referred to East Gauss Boaga projection Roma40 Datum.

| Meteo Station | E | N |
|---|---|---|
| BRUGNERA | 2329618 | 5087890 |
| CAPRIVA | 2404728 | 5090481 |
| CERVIGNANO | 2390898 | 5078684 |
| CIVIDALE | 2397830 | 5104229 |
| CODROIPO | 2365213 | 5090727 |
| FAEDIS | 2392735 | 5110354 |
| FAGAGNA | 2371831 | 5107055 |
| GEMONA | 2375280 | 5124822 |
| GRADISCA | 2402238 | 5082963 |
| GRADO | 2400052 | 5063524 |
| LIGNANO | 2375762 | 5062618 |
| PALMANOVA | 2368690 | 5074335 |
| PORDENONE | 2340288 | 5091525 |
| SAN VITO | 2350508 | 5084781 |
| TALMASSONS | 2376895 | 5082663 |
| UDINE | 2382790 | 5099513 |
| VIVARO | 2347472 | 5104972 |

Tab. 5.2. Transport and conversion parameter.

| Parameter | Unit | Value | Source |
|---|---|---|---|
| *Biomass transport from field (cell) to collecting centre by tractor and trailer* | | | |
| Cost | €·$t^{-1}$ biomass | depending from kilometric range (mean 0.15 €·$t^{-1}$·$km^{-1}$) | market price |
| Energy | MJ·$km^{-1}$·$t^{-1}$ | 5.27 | Ecoinvent database 2.1 |
| $CO_2$ emission | kg $CO_2$ eq·$km^{-1}$·$t^{-1}$ | 0.31 | Ecoinvent database 2.1 |
| *Biomass transport from collecting centre to processing plant by lorry >32t* | | | |
| Cost | €·$t^{-1}$ biomass | depending from kilometric range (mean 0.15 €·$t^{-1}$·$km^{-1}$) | market price |
| Energy | MJ·$km^{-1}$·$t^{-1}$ | 1.78 | Ecoinvent database 2.1 |
| $CO_2$ emission | kg $CO_2$ eq·$km^{-1}$·$t^{-1}$ | 0.10 | Ecoinvent database 2.1 |
| *Conversion* | | | |
| Biofuel Yield | L·$t^{-1}$ biomass | 160 | experimental result |
| Coproduct value | €·$L^{-1}$ biofuel | 0.01 | experimental result |
| Conversion costs | €·$L^{-1}$ biofuel | 0.07 | Siemons *et al.*, 2004 |
| Energy content biofuel | MJ·$L^{-1}$ biofuel | 32.93 | Hill *et al.*, 2006 |
| Coproduct credit | MJ·$L^{-1}$ biofuel | 21.94 | Hill *et al.*, 2006 |
| Conversion energy | MJ·$L^{-1}$ biofuel | 8.08 | Hill *et al.*, 2006 |

Tab. 5.3. Crop management types for soybean cultivation.

| Soybean High Input | | Soybean Low Input | |
|---|---|---|---|
| *Doy* | *Practises scheduling* | *Doy* | *Practises scheduling* |
| 91 | Plowing | 91 | Plowing |
| 110 | Harrowing | 110 | Harrowing |
| 125 | Planting | 125 | Planting |
| 125 | Mineral Fertilisation (Diammonium phosphate, 100 kg) | 152 | Herbicide treatment (Metolachor, 2 kg/ha) |
| 152 | Herbicide treatment (Metolachor, 2 kg/ha) | 182 | Hoeing |
| 172 | Herbicide treatment (Fomesafen, 0.5 kg/ha + Bentazone, 0.5 kg/ha) | 268 | Harvest |
| 182 | Hoeing | | |
| 186 | Irrigation (30 mm/h) | | |
| 227 | Irrigation (30 mm/h) | | |
| 268 | Harvest | | |

Doy = day of the year

most widespread and adapted energy crop cultivated on the territory (Santamaria *et al.*, 2007).

The combination between soil types (23) and climate conditions (17) produced 137 pedo-climatic typologies.

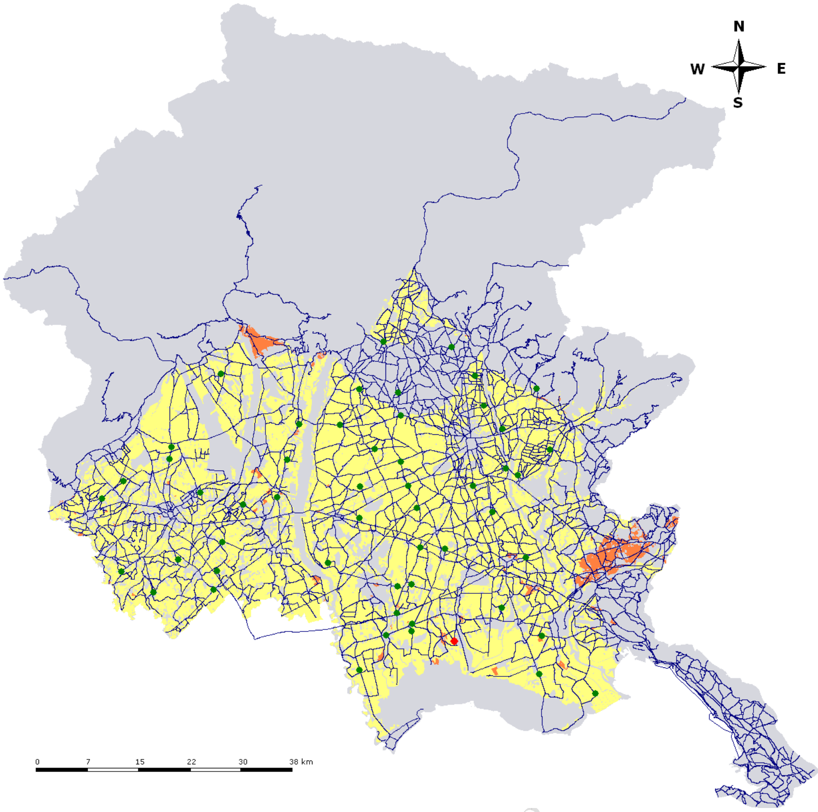


Fig. 5.4. Land use and logistic network in the study area: drained arable area (yellow area), complex cultivation patterns with scattered settlement (orange area), road (regional technical map of FVG - scale 1:5000, blue line), collecting centre (green point) and processing plant (red point).

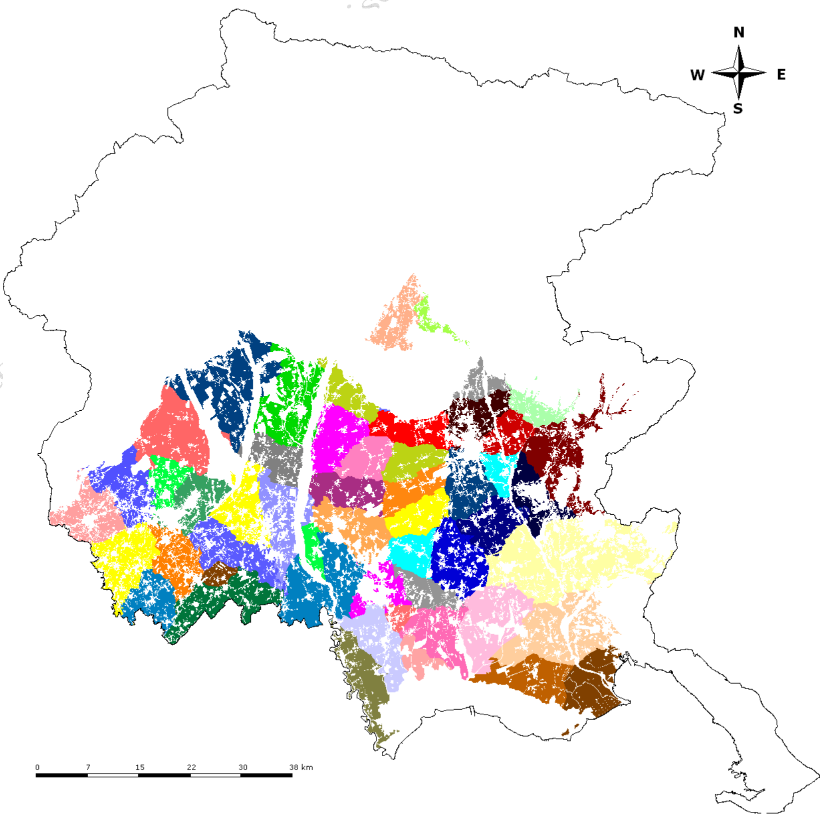


Fig. 5.5. Collecting areas.

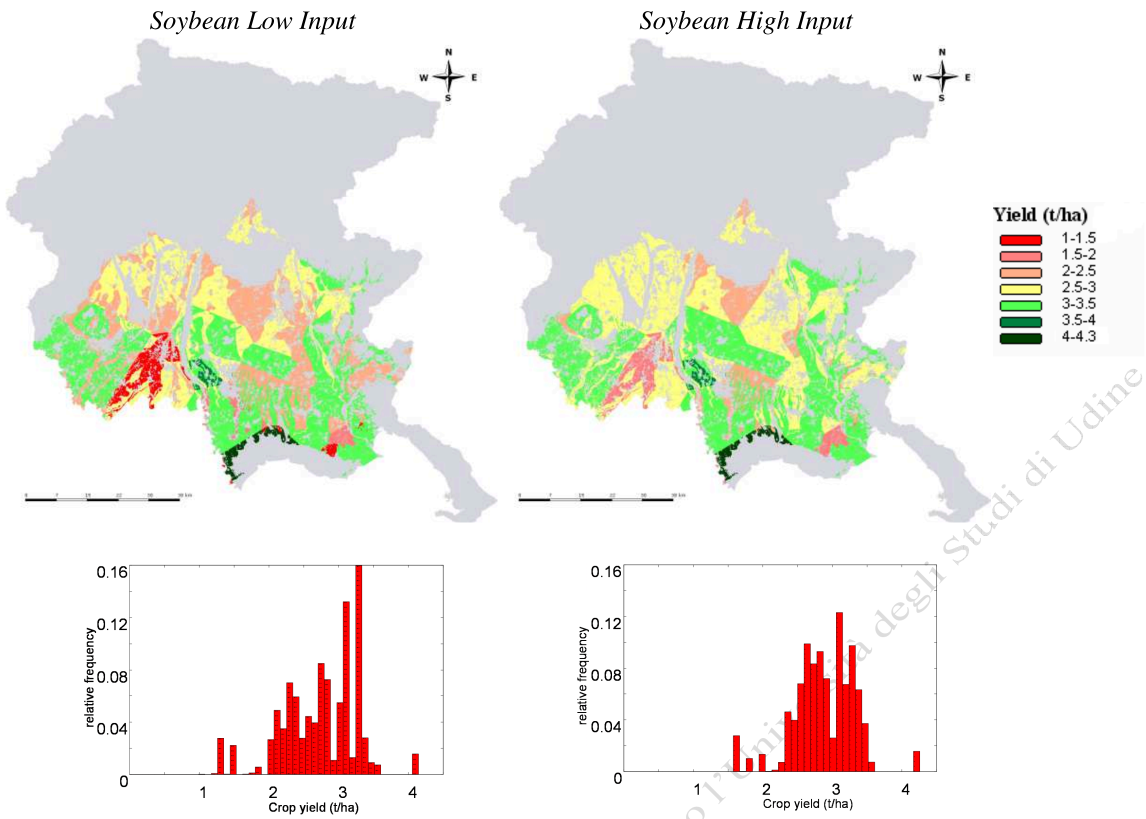


Fig. 5.6. Simulated soybean yield ($t \cdot ha^{-1}$) in the study area for two scenarios, low and high input level.

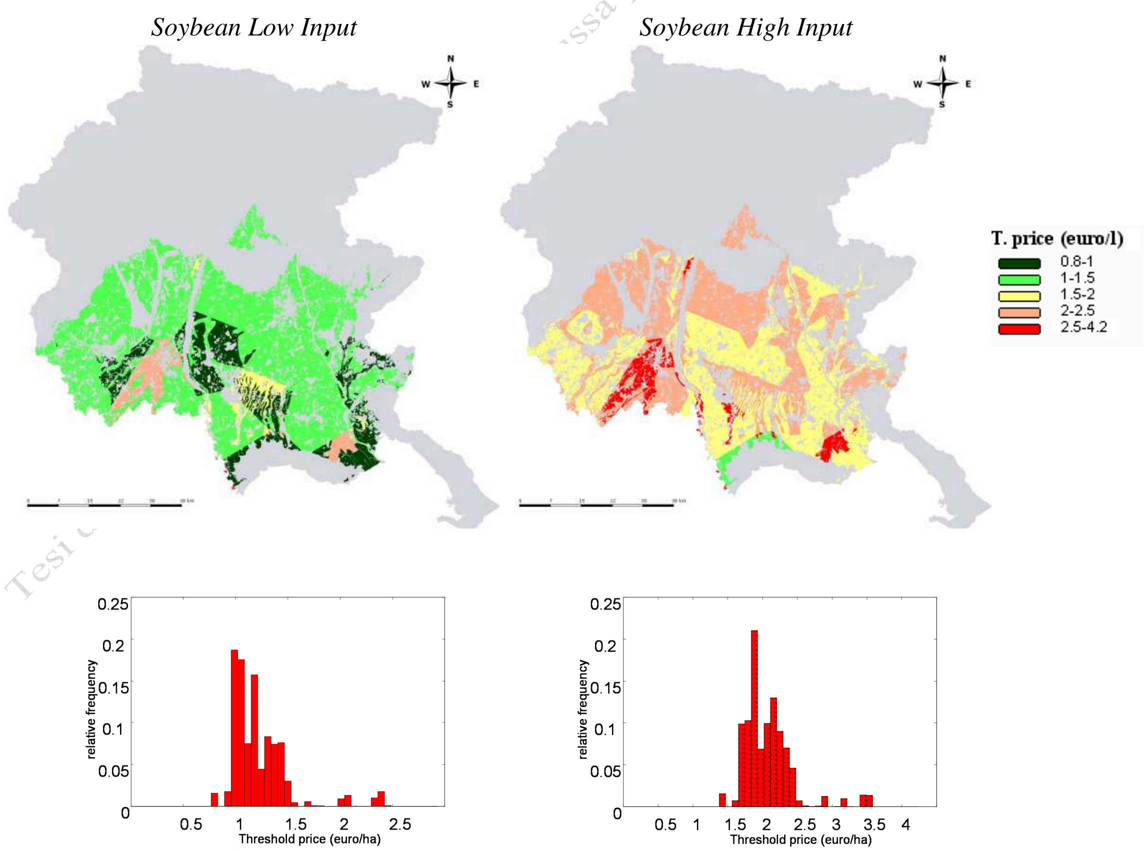


Fig. 5.7. Simulated biofuel threshold price ($€ \cdot L^{-1}$) for two scenario, low and high input soybean cultivation.

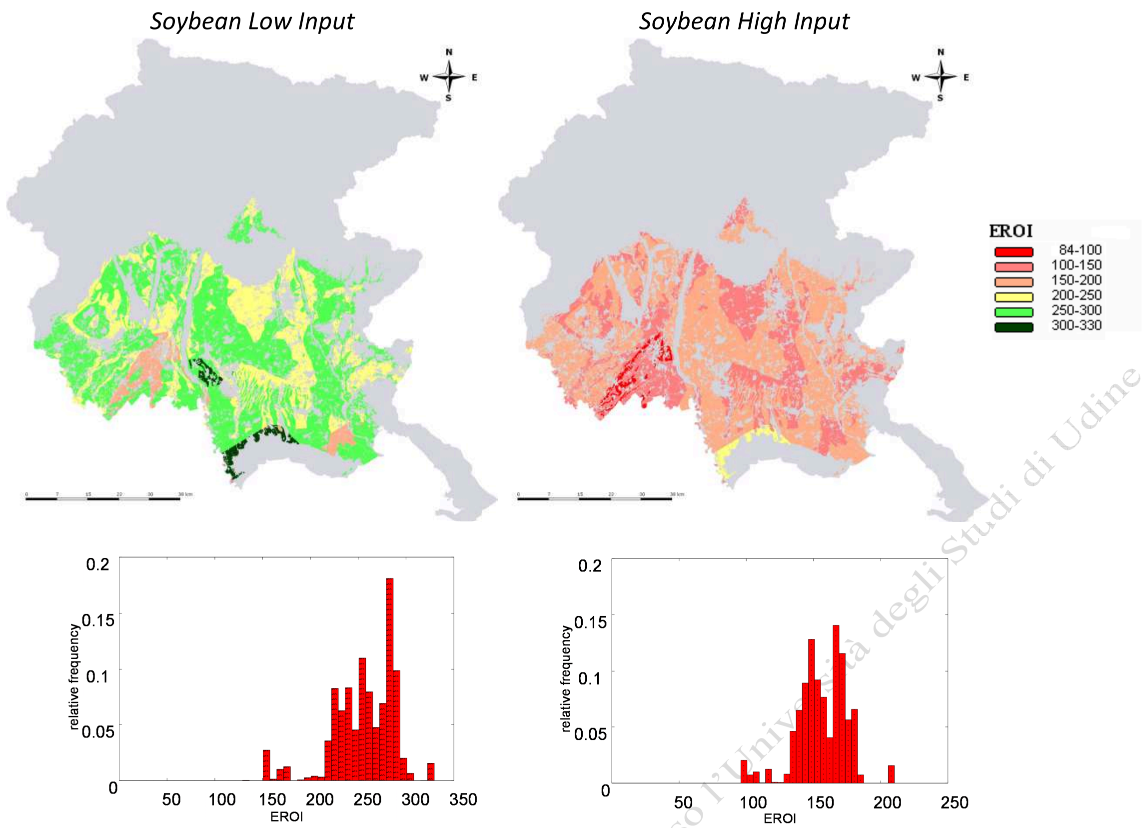


Fig. 5.8. Simulated EROI for biofuel production from soybean cultivation and two scenario, low and high input level conditions.

Tab. 5.4. Results for the simulated soybean yield, relative threshold price and EROI for two input levels.

| | Low input | | | | High input | | | |
|---|---|---|---|---|---|---|---|---|
| | *Min* | *Max* | *Mean* | *SD* | *Min* | *Max* | *Mean* | *SD* |
| Crop yield (t ha$^{-1}$) | 1.04 | 4.15 | 2.75 | 0.54 | 1.34 | 4.26 | 2.88 | 0.44 |
| Threshold price (€ L$^{-1}$) | 0.80 | 2.93 | 1.22 | 0.29 | 1.39 | 4.22 | 2.07 | 0.36 |
| EROI | 130.78 | 329.57 | 256.42 | 32.65 | 84.39 | 210.22 | 156.55 | 18.71 |

Crop yields (dry weight), threshold prices, energy return on investment (EROI) for the study area are shown respectively in Fig. 5.6, Fig. 5.7 and Fig. 5.8. Results are derived from the mean of 100 independent simulations. A frequency histogram of variable classes is associated to every map. The statistics for the variables and for the two input level conditions are presented in Tab. 5.4.

High input soybean cultivation ensures lower production variability over the territory than low input level, and for the analysed scenario a slight increase of the average production.

Nonetheless, high input levels, requiring higher agronomic costs, negatively influence the biofuel prices at the end of the chain, becoming less convenient.

As far as EROI is concerned, low input conditions allow to obtain widespread energy gains on the territory from the whole agro-energy chain instead energy costs for high input management are not always counterbalanced by the gains.

## 5.4. Conclusions

The presented software evaluates land suitability for agro-energy purposes taking into account five sources of variability: soil characteristics and availability, climate, road network, agricultural techniques and crop. The first three factors are site-specific for the territory and are a part of variability that is to be considered, but independent from the farmer choices. The latter two are variability sources directly controllable by agronomic choices and so are optimisable.

The software doesn't consider only spatial variability but also variability on time scale summarizing results of multiple independent simulation for each cell of the study area.

Case study analysis proves that low input soybean management techniques let to reach the better results in terms of energy gains in the FVG plain. Moreover, low input conditions allow to achieve the most convenient biofuel threshold prices to counterbalance chain costs considering a cooperative chain organisation.

The software allows comparison of alternative energy crops in a specific territory. In this sense, the future evolution of the application will be based on: 1) the calculation of the environmental balance of the whole agro-energy chain in terms of $CO_2$ emissions and leached nitrogen; 2) the comparison of the performance of different energy crops on the same territory; 3) the identification of the optimal use of the agricultural techniques to maximize the energy balances for each cell (production problem); 4) the optimal distribution of the collecting points in the territory (logistic problem).

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## List of Abbreviations

| | |
|---|---|
| *AC* | Agricultural costs (€·ha$^{-1}$) |
| *AE* | Energy inputs agricultural phase (GJ·ha$^{-1}$) |
| *BE* | Biofuel energy content (GJ·ha$^{-1}$) |
| *BY* | Biofuel yield (L·ha$^{-1}$) |
| *CCen* | Grid map cell centroid |
| *CC* | Conversion costs (€·ha$^{-1}$) |
| *CE* | Conversion energy consumption (GJ·ha$^{-1}$) |
| *ChC* | Chain cost (€·ha$^{-1}$) |
| *CopE* | By-product energy content (GJ·ha$^{-1}$) |
| *CopV* | By-product value (€·ha$^{-1}$) |
| *CP* | Collecting point |
| *CSS* | Cropping System Simulator |
| *EROI* | Energy Return On Investment |
| *PA* | Homogenous areas for pedological and climatic conditions |
| *PP* | Processing plant |
| *TC* | Transport costs (€·ha$^{-1}$) |
| *TE* | Transport energy consumption (GJ·ha$^{-1}$) |
| *TEm* | Transport energy emissions (t$CO_2$eq·ha$^{-1}$) |
| *TP* | Threshold price (€·L$^{-1}$) |

# 6

# General conclusions and future perspectives

Fabrizio Ginaldi

This thesis analysed two different agro-energy chains: the short chain, using an LCA approach, and the medium long chain, developing an integrated approach that uses a crop model. During the cropping system analysis, climate uncertainty needs to be taken into account.

The obtained validation results for the weather generator *Climak 3* presented in Chapter 2, shows that it can be considered as sufficiently accurate tool for the generation of meteorological data for temperate and cold climates. In general, the behavior of the model has been satisfactory but some aspects are still to be improved. A new version (*Climak 4,* now under development) will address these limitations introducing new algorithm for temperatures and radiation parameter estimation and generation. The results derived from the comparison of *Climak 4* with another stochastic weather generator (*LARS WG v.5*) proved its reliability. The further works will be focused on the improvement of the estimation and/or generation procedures of evapotranspiration and radiation data. Moreover, it will be necessary to develop issues concerning downscaling of meteorological variables (from monthly to daily and from daily to hourly) and the generation of extreme events.

For cultivation of energy crops, which do not have to compete with food production, only marginal lands should be reserved. The difficulty stays on establishment of objective criteria to define marginal area, probably on the basis of profitability. The two analysed agro-energy chain types have to be integrated on the territory according the specific suitability of an area for one of these alternative choices.

In agro-energy chains, for the analysed conditions, low input cropping conditions allow to obtain the best performance in terms of energy returns on investment.

At the farm level, energy production deriving from the low input cropping system is substantially cleaner than the use of the electricity mix. Impacts of N and P losses to aquatic and terrestrial ecosystems deriving from fertiliser overuse have to be carefully under control. Overall, the diffusion of the precision agriculture, in which fertilizer application rates and timing are adjusted differentially across a field to meet crop needs, will increase agricultural efficiency and decrease adverse effects on the environment.

At the territorial level, considering a cooperative organisation of the agro-energy chain, low input cultivations enable to achieve more favourable biofuel market price than high input.

The last chapter presents a software application (*X-land*) that uses an integrated and interdisciplinary approach to analyse and planning agro-energy chains at regional level, considering soil productivity, climate and location, with respect to intermediate collecting centres, processing plants and road network. The strength of the software is the use of the simulation models able to treat system complexity taking into account different uncertainty and variability sources. The further works will be focused on the calculation of the $CO_2$ eq chain balance and on the implementation of methodologies to compare alternative scenarios.

# Annex I

## SEMoLa scripts for the validation of weather generators

Script for graphical comparison of generated and historical daily meteo data

SEMoLa Command line:

```
CompareMeteo Italy.dct Italygen.dct C:\WorkingFolder
```

```
script def CompareMeteo
 ' compare generated and historical meteorological daily dataset
 ' each dataset contain doy rain tmin tmax rg etr winds
 ' %1% historical data file
 ' %2% generated data file
 ' %3% working folder
set wd %3%
scalar drop drop
log using ClimakValid.log
log off
' === historical dataset ===
use %1% clear
set capture on drop day
drop month set capture off
dateconv doy gen(month,day) scalar FlagWinds=vexist("winds") cif FlagWinds :
collapse mean(Rain,Tmin,Tmax,Rg,Etr,Winds) sd(Rain,Tmin,Tmax,Rg,Etr,Winds)
by(month) saving(bufdata1) replace
cif FlagWinds=0 : collapse mean(Rain,Tmin,Tmax,Rg,Etr) sd(Rain,Tmin,Tmax,Rg,Etr)
by(month) saving(bufdata1) replace
' === generated dataset ====
use %2% clear
set capture on drop day
drop month
set capture off
dateconv doy gen(month,day)
cif FlagWinds : collapse mean(Rain,Tmin,Tmax,Rg,Etr,Winds)
sd(Rain,Tmin,Tmax,Rg,Etr,Winds) by(month) saving(bufdata2) replace
cif FlagWinds=0 : collapse mean(Rain,Tmin,Tmax,Rg,Etr) sd(Rain,Tmin,Tmax,Rg,Etr)
by(month) saving(bufdata2) replace
use bufdata1.dct clear
merge bufdata2.dct by(month) suff(Gen)
 ' === labels ====
header varlab Rain_aGen "Rain (generated)"
header varlab Tmin_aGen "Tmin (generated)"
header varlab Tmax_aGen "Tmax (generated)"
header varlab Rg_aGen "Rg (generated)"
header varlab ETr_aGen "Etr (generated)"
cif FlagWinds : header varlab Winds_aGen "Winds (generated)"
header varlab Rain_sGen "Rain sd (generated)"
header varlab Tmin_sGen "Tmin sd (generated)"
header varlab Tmax_sGen "Tmax sd (generated)"
header varlab Rg_sGen "Rg sd (generated)"
header varlab ETr_sGen "Etr sd (generated)"
cif FlagWinds : header varlab Winds_sGen "Winds (generated)"
' ==== plot Means ==============
plot Rain_a Rain_aGen month con pause 1
plot Tmax_a Tmin_a Tmax_aGen Tmin_aGen month con
pause 1
plot Rg_a Rg_aGen month con
pause 1
plot Etr_a Etr_aGen month con
pause 1
cif FlagWinds : plot Winds_a Winds_aGen month con
pause 1
' plot Rain_a Rain_aGen month con output(jpeg) saving(Mrain)
' pause 1
' plot Tmax_a Tmin_a Tmax_aGen Tmin_aGen month con output(jpeg) saving(MTemp)
' pause 1
' plot Rg_a Rg_aGen month con output(jpeg) saving(Mrg)
' pause 1
' plot Etr_a Etr_aGen month con output(jpeg) saving(Metr)
```

```
' pause 1
' cif FlagWinds : plot Winds_a Winds_aGen month con output(jpeg) saving(Mwinds)
' pause 1
 ' ==== plot SD ==============
plot Rain_s Rain_sGen month con pause 1
plot Tmax_s Tmin_s Tmax_sGen Tmin_sGen month con
pause 1
plot Rg_s Rg_sGen month con
pause 1
plot Etr_s Etr_sGen month con
pause 1
cif FlagWinds : plot Winds_s Winds_sGen month con
pause 1
' plot Rain_s Rain_sGen month con output(jpeg) saving(Srain)
' pause 1
' plot Tmax_s Tmin_s Tmax_sGen Tmin_sGen month con output(jpeg) saving(STemp)
' pause 1
' plot Rg_s Rg_sGen month con output(jpeg) saving(SRg)
' pause 1
' plot Etr_s Etr_sGen month con output(jpeg) saving(Setr)
' pause 1
' cif FlagWinds : plot Winds_s Winds_sGen month con output(jpeg) saving(Swinds)
' pause 1
' ==== display ==============
replace Rain_a=round(rain_a,2)
replace Rain_aGen=round(rain_aGen,2)
replace Tmax_a=round(Tmax_a,2)
replace Tmax_aGen=round(Tmax_aGen,2)
replace Tmin_a=round(Tmin_a,2)
replace Tmin_aGEN=round(Tmin_aGen,2)
replace Rg_a=round(Rg_a,2)
replace Rg_aGEN=round(Rg_aGen,2)
replace Etr_a=round(ETr_a,2)
replace Etr_aGEN=round(ETr_aGen,2)
cif FlagWinds : replace winds_a=round(Winds_a,2)
cif FlagWinds : replace winds_aGEN=round(Winds_aGen,2) replace
Rain_s=round(rain_s,2)
replace Rain_sGen=round(rain_sGen,2)
replace Tmax_s=round(Tmax_s,2)
replace Tmax_sGen=round(Tmax_sGen,2)
replace Tmin_s=round(Tmin_s,2)
replace Tmin_sGEN=round(Tmin_sGen,2)
replace Rg_s=round(Rg_s,2)
replace Rg_sGEN=round(Rg_sGen,2)
replace Etr_s=round(ETr_s,2)
replace Etr_sGEN=round(ETr_sGen,2)
cif FlagWinds : replace winds_s=round(Winds_s,2)
cif FlagWinds : replace winds_sGEN=round(Winds_sGen,2)
save bufdata1 replace
log on order Rain_a Rain_aGen Rain_s Rain_sGen _ Tmax_a Tmax_aGen Tmax_s _
Tmax_sGen Tmin_a Tmin_aGen Tmin_s Tmin_sGen _
Rg_a Rg_aGen Rg_s Rg_sGen _
Etr_a Etr_aGen Etr_s Etr_sGen
list
log off
log close
script drop
end script
```

Script for comparing cumulative density function of generated and historical daily meteo data

SEMoLa Command line:

```
KS Italy.dct Italygen.dct Tmin 1 Ita
```

```
script def KS
'-------------------------------------------------
' Compare cumulative density function (CDF) of the same generated and historical
variable
' Input:
' %1% historical data file
' %2% generated data file
' %3% variable to compare
' %4% month
' %5% acronym for country

use %1% clear
keep month %3%
keep if month=%4%
keep %3%
cumulate %3% gen(Cdf%3%_o)
save %3%_o.dct replace

use %2% clear
keep month %3%
keep if month=%4%
keep %3%
cumulate %3% gen(Cdf%3%_g)
save %3%_g.dct replace

'-------------------------------------------------
'Plot two cumulative frequency functions
use %3%_g.dct
rename %3% Ge
rename Ge %3%
save replace

use %3%_o.dct
rename %3% Os
rename Os %3%
save replace

use %3%_g.dct
append %3%_o.dct
header varlab Cdf%3%_g "%3%_%4%_Ge"
header varlab Cdf%3%_o "%3%_%4%_Os"
plot Cdf%3%_g Cdf%3%_o %3% saving(Cdf_%5%_%4%_%3%)
save Cdf%3%_%4%.dct
erase Cdf%3%_%4%.dct
'-------------------------------------------------
' Kolmogorov-Smirnov test between cumulative functions
use %3%_o.dct clear
rename %3% %3%_o
save replace

use %3%_g.dct clear
rename %3% %3%_g
save replace

merge %3%_o.dct
save replace

ksmirnov %3%_o=%3%_g
scalar d_%3%_%4% =_D
scalar p_%3%_%4% =_Dexact
```

```
erase %3%_g.dct
erase %3%_o.dct

end script
```

Script for drawing QQPlot of historical and generated daily meteo data

SEMoLa Command line:

`QQplot Italy.dct Italygen.dct Tmin month 1 Ita`

```
script def QQplot
'Scripts for drawing QQplot of generated vs historial meteo daily data
'Fields in input files:
' - Variable of interest
' - Month (from 1 to 12) or Season (1 to 4)
'   season code:
'   1 - mar, apr, may
'   2 - jun, jul, aug
'   3 - sep, oct, nov
'   4 - dec, jan, feb

'Arguments:
'%1% histoical data file
'%2% generated data file
'%3% variable to compare
'%4% "month" or "season" option
'%5% month (1 to 12) o stagione (1 to 4)
'%6% acronym for cuntry

use %1% clear
keep %3% %4% keep if %4%=%5%
drop %4% rename %3% %3%_Os
save QQObs.dct replace
use %2% clear
keep %3% %4%
keep if %4%=%5%
drop %4% rename %3% %3%_Ge
save QQGen.dct replace
use QQObs.dct
merge QQGen.dct
cumulate %3%_Os gen(Cdf%3%_Os)
cumulate %3%_Ge gen(Cdf%3%_Ge)
class Cdf%3%_Os auto(100,0,0.01) gen(Cdf%3%_OsClass)
class Cdf%3%_Ge auto(100,0,0.01) gen(Cdf%3%_GeClass)
collapse max(%3%_Os) by(Cdf%3%_OsClass) saving(QQ%3%_Os) replace
collapse max(%3%_Ge) by(Cdf%3%_GeClass) saving(QQ%3%_Ge) replace
save QQObs.dct replace use QQ%3%_Os.dct merge QQ%3%_Ge.dct
' save QQdata
'regress %3%_Os_x %3%_Os_x
header varlab %3%_Ge_x "%3%_Ge"
header varlab %3%_Os_x "%3%_Os"
plot %3%_Ge_x %3%_Os_x func(x) xrange(,15) yrange(,15)
saving(QQ_%6%_%4%_%5%_%3%)
erase QQObs.dct
erase QQGen.dct
erase QQ%3%_Os.dct
erase QQ%3%_Ge.dct

end script
```

# Annex II

## *Climak 4*: a robust weather generator, usable on global scale

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## AII.1. Introduction

Weather generators are used to produce climatic input data for impact models, such as cropping system models (Semenov and Porter, 1995). Climate assessment studies on global scale require robust generators able to represent different climate types, an hardly available feature. *Climak 4* derives from the development of previous models (Danuso, 2002; Rocca *et al.*, 2012) for the stochastic generation of meteorological series from the historical ones. It includes applications for parameter estimation, generation and results evaluation and has been implemented with the aim of the global scale usability. *Climak 4* has been compared with one of the most common weather generator *LARS WG v.5* (Semenov and Barrow, 1997).

## AII.2. Methodology

Weather generator performance is evaluated on the basis of its capability to produce series with the same statistical properties of the historical data (Semenov *et al.*, 1998). The study considers three stations with different climate type (Spain, Bulgaria and Argentina) and four climate variables: maximum (*Tmax*) and minimum temperature (*Tmin*), precipitation (*Rain*) and radiation (*Rad*). Two comparisons were done between *Climak 4* and *LARS WG*: 1) graphical comparison on generated data statistics: for each station a 100 years series has been produced with each weather generator and then monthly averages, daily and inter-annual variability of historical and generated series were compared; 2) for each generated variable and station and for both the weather generators, it was calculated a mean square error on monthly averages ($MSE_\mu$) and on daily variability ($MSE_\sigma$) between generated and historical series according to equations (a) and (b). Mean square error was estimated by a Monte Carlo method comparing, for each station, 1000 generated series ($s$), each one of 100 years, with the historical data.

$$\text{(a)}\quad MSE_\mu = \sum_{i=1}^{12} \frac{1}{\sigma_{\mu Obs_i}} \cdot \frac{1}{s} \sum_{j=1}^{s} (\mu Gen_{ij} - \mu Obs_i)^2$$

$$\text{(b)}\quad MSE_\sigma = \sum_{i=1}^{12} \frac{1}{\sigma_{\sigma Obs_i}} \cdot \frac{1}{s} \sum_{j=1}^{s} (\sigma Gen_{ij} - \sigma Obs_i)^2$$

where: $MSE_\mu$ = mean square error on the averages ($\mu_i$); $MSE_\sigma$ = mean square error on the standard deviations ($\sigma_i$); $i$ = month (1→12); $\sigma_{\mu Obsi}$ = inter-annual variability of the *i-th* monthly average in historical data; $\sigma_{\sigma Obsi}$ = inter-annual variability of the *i-th* monthly variability in historical data; $s$ = number of generated series; $j$ = generated series index; $\mu Gen_{ij}$ = monthly average of the *i-th* month of the *j-th* generated series; $\mu Obs_i$ = monthly average of the *i-th* month of the historical series; $\sigma Gen_{ij}$ = variability of the *i-th* month of the *j-th* generated series; $\sigma Obs_i$ = variability of the *i-th* month of the historical series.

## AII.3. Results and Discussion

Weather generators showed similar performances to reproduce variables monthly average, whereas *Climak 4* is better in the simulation of the variability (Fig. AII.1). Mean square errors of the generators for variability and monthly averages of *Tmax*, *Tmin* and

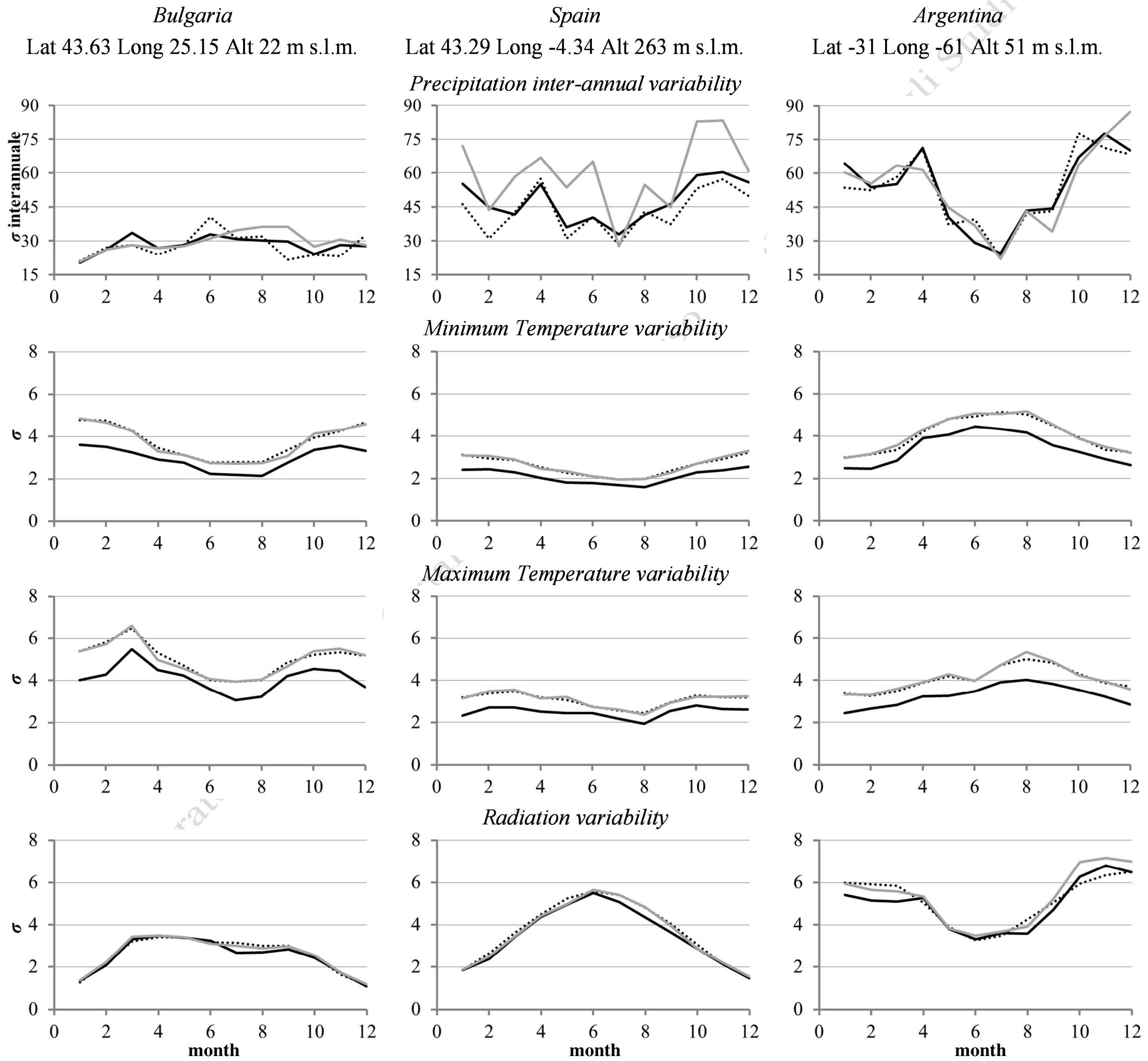


Fig. AII.1. Comparison between the variability of the generated data from *Climak 4* (dotted line) and *LARS WG* (black line) with those of the historical series (grey line) for three stations climatically extremely different. It was compared inter-annual variability of total monthly precipitation (*σ inter-annual*), daily variability (*σ*) of radiation, maximum and minimum temperature.

Tab. AII.1. Mean square error for the average ($MSE_{\mu}$) and the variability ($MSE_{\sigma}$) of the generated variables from *Climak 4* and *LARS WG* obtained from comparison with historical data.

| | $MSE_{\mu}$ *Tmax* | | $MSE_{\mu}$ *Tmin* | | $MSE_{\mu}$ *Rad* | | $MSE_{\sigma}$ *Tmax* | | $MSE_{\sigma}$ *Tmin* | | $MSE_{\sigma}$ *Rad* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stazion | Climak4 | LARS WG | Climak4 | LARS WG | Climak4 | LARS WG | Climak4 | LARS WG | Climak4 | LARS WG | Climak4 | LARS WG |
| Bulgaria | 0.02 | 0.02 | 0.03 | 0.01 | 0.15 | 0.03 | 0.03 | 0.89 | 0.03 | 0.74 | 0.02 | 0.03 |
| Spain | 0.03 | 0.03 | 0.03 | 0.03 | 0.12 | 0.10 | 0.01 | 1.06 | 0.01 | 1.16 | 0.03 | 0.26 |
| Argentina | 0.07 | 0.03 | 0.06 | 0.03 | 0.32 | 0.09 | 0.01 | 0.94 | 0.02 | 0.64 | 0.22 | 0.15 |

*Rad* for all the stations are in Tab. AII.1. Errors are similar for the averages whereas *Climak 4* shows a lower error in reproducing the *Tmin* and *Tmax* variability.

## AII.4. Conclusions

*Climak 4* showed excellent performance to simulate climate variability of meteo series of extremely different localities, proposing itself as a reliable tool to use with impact model. *Climak 4* is freely downloadable on http://www.dpvta.uniud.it/~Danuso/docs/ Climak/homep.htm.

## AII.5. Acknowledgements

Thanks go to prof. Corrado Lagazio and prof. Paolo Vidoni of the Department of Statistical Sciences of the University of Udine for the help in the development of methodologies for stochastic model comparison.

## AII.6. References

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Semenov M., Porter J., 1995. Climatic variability and the modelling of crop yields. *Agr. Forest. Meteorol.*, 73:265-283.

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# Annex III

## SemGrid script for the evaluation of land suitability for energy crops

Fabrizio Ginaldi

SemGrid Command line:

```
Xland Meteo.dct mais 0.5 0.5 100 C:\WorkingFolder
Tracciati.dxf Intersezioni_Stradali.csv Consorzi2010.txt 100
Fiumi.fiu
```

```
script def Xland
'SemGrid 1.4.5 script (10-25-2011 15:06:55)
'Purpose: Land suitability for energy crops
'Arguments:
'%1% list of meteo station .dct or .csv (e.g.Meteo.dct) . The file must contain
six
'columns: Station name, X coordinate, Y coordinate, Longitude, Latitude,
Altitude. To
'each station have to correspond a historical meteo file with the same name in
the
'working folder. Station name on meteo station file has not to have an extension
'%2% crop e.g. mais, soia
'%3% kdw, tolerated water stress, increasing the percentage increases the
potential 'water lack tolerated, e.g. 0.2 high input and low stress, 0.5 medium
input, 0.8 low input
'%4% kdn, fertilization level, increasing the percentage increases the potential
'fertilisation lack tolerated, e.g. 0.2 high input, 0.5 medium input, 0.8 low
input
'%5% grid cell dimension
'%6% working folder path
'%7% road graph file .dxf without extension (e.g. Tracciati.dxf)
'%8% road junction file .csv (e.g. Intersezioni_Stradali.csv)
'%9% collecting centre coordinates file .txt or .csv (e.g. Consorzi2010.txt)
'%10% years to simulate
'%11% eventual obstacle file (e.g.Fiumi.fiu)

'PROCEDURE STEPS:
'1) Pedo-climatic characterization
'2) Crop simulation
'3) Logistic optimization
'4) Conversion
'5) Final balances

'--------Pedo-climatic characterisation of each grid cell-------------
'Inputs:
'1) %1% list of meteo station .dct o .csv;
'2) Moland map 1:25.000 (e.g. Mol_ras_100.txt)
'3) AWC map
'4) CSC map
'5) texture map
'6) permeability map
'7) historical daily meteo series for stations in %1% in .dct o .csv format.

'Outputs:
'ArableArea.bmp arable area map
'AWC.bmp AWC map
'CSC.bmp CSC map
'Gran.bmp texture map
'Perm.bmp permeability map
'Meteo.bmp Voronoi spazialization of meteo station
'Code_soil.bmp soil map
'Comb_soil_met.bmp pedoclimatic areas
'File Combinazioni.dct that contains the pedoclimatic type of each cell
(comb_sm, e.g. '10_1123) and its area m2 (Area)
'Generated daily meteo series
'All the maps are exported in .txt format

use %1%
```

```
gen int Code_Meteo=_i
save Meteo.dct replace
drop all
set maxcats 150 'set of the max number of map categories 150

'Importation of the land use map in .txt format and selection of
'arable areas (codes:
'21 = "Seminativi in aree non irrigue",
'30 = "Sistemi colturali e particellari complessi senza insediamenti sparsi"
'36 = "Sistemi colturali e particellari complessi con insediamenti sparsi"
import Mol_ras_100.txt as(ArcGis) gen(Mol_ras_100) type(int) 'importazione della
Moland '1.25.000
gen int ArableArea=Mol_ras_100 if Mol_ras_100=21|Mol_ras_100=30|Mol_ras_100=36
legend def ArableArea 21 65535 "Seminativi in aree non irrigue"
legend def ArableArea 30 33023 "Sistemi colturali e particellari complessi senza
insediamenti sparsi"
legend def ArableArea 36 255 "Sistemi colturali e particellari complessi con
insediamenti sparsi"
legend savepal ArableArea ArableArea

drop Mol_ras_100

'Importation of the soil maps
'awc (mm) three classes                    1=1-74 2=75-150 3=151-337
'csc (meq/100g) three classes              1= <5 2= 5-10 3= >10
'perm (mm/h) three classes                 1= <0.36 2= 0.36-36 3= >36
'gran three classes                        1=fine 2=media 3=grossolana
import awc_ras_100.txt as(ArcGis) gen(awc_ras_100) type(int) 'import AWC map
replace awc_ras_100=. if awc_ras_100<>1&awc_ras_100<>2&awc_ras_100<>3
legend def awc_ras_100 1 255 "Bassa"
legend def awc_ras_100 2 65535 "Media"
legend def awc_ras_100 3 32768 "Alta"
legend savepal awc_ras_100 AWC
map awc_ras_100 labels compass(90,8) ruler(4,95) saving(AWC.bmp) 'AWC map .bmp
export awc_ras_100 as(ArcGis) saving(awc_ras_100_mod) replace

import csc_ras_100.txt as(ArcGis) gen(csc_ras_100) type(int) 'import CSC map
replace csc_ras_100=. if csc_ras_100<>1&csc_ras_100<>2&csc_ras_100<>3
legend def csc_ras_100 1 255 "Bassa"
legend def csc_ras_100 2 65535 "Media"
legend def csc_ras_100 3 32768 "Alta"
legend savepal csc_ras_100 CSC
map csc_ras_100 labels compass(90,8) ruler(4,95) saving(CSC.bmp) 'CSC map .bmp
export csc_ras_100 as(ArcGis) saving(csc_ras_100_mod) replace

import gran_ras_100.txt as(ArcGis) gen(gran_ras_100) type(int) 'import texture
map
replace gran_ras_100=. if gran_ras_100<>1&gran_ras_100<>2&gran_ras_100<>3 legend
def gran_ras_100 1 255 "Fine"
legend def gran_ras_100 2 65535 "Media"
legend def gran_ras_100 3 32768 "Grossolana"
legend savepal gran_ras_100 Gran
map gran_ras_100 labels compass(90,8) ruler(4,95) saving(Gran.bmp) 'texture map
.bmp
export gran_ras_100 as(ArcGis) saving(gran_ras_100_mod) replace

import perm_ras_100.txt as(ArcGis) gen(perm_ras_100) type(int) 'import
permeability map
replace perm_ras_100=. if perm_ras_100<>1&perm_ras_100<>2&perm_ras_100<>3
legend def perm_ras_100 1 255 "Bassa"
legend def perm_ras_100 2 65535 "Media"
legend def perm_ras_100 3 32768 "Alta"
legend savepal perm_ras_100 Perm
map perm_ras_100 labels compass(90,8) ruler(4,95) saving(Perm.bmp) 'permeability
map .bmp
export perm_ras_100 as(ArcGis) saving(perm_ras_100_mod) replace
```

```
save Xland.grp replace

'Meteo station spazialization
insert X Y Code_meteo into(Code_meteo) using(Meteo.dct)
spatial Code_meteo gen(Code_meteo) met(v)

'Definition of the number of pedo-climatic areas
'Saving of Combinazioni.dct file with combinations and their frequency
recast int Code_meteo force
gen int Meteo_map=Code_meteo if ArableArea<>"."&awc_ras_100<>"."
legend loadpal Meteo_map 256_colors.pal
legend loadlab Meteo_map input(Meteo.dct,Code_Meteo,Stazione)
map Meteo_map labels compass(90,8) ruler(4,95) saving(Meteo.bmp) 'meteo map .bmp
export Meteo_map as(ArcGis) saving(Meteo_map) replace
drop Meteo_map

gen int
Code_soil=(awc_ras_100*1000)+(csc_ras_100*100)+(gran_ras_100*10)+perm_ras_100 if
ArableArea<>"."&awc_ras_100<>"."&csc_ras_100<>"."&gran_ras_100<>"."&perm_ras_100
<>"."
legend loadpal Code_soil 256_colors.pal
map Code_soil labels compass(90,8) ruler(4,95) saving(Code_soil.bmp) 'soil map
.bmp
export Code_soil as(ArcGis) saving(Code_soil.bmp) replace

gen int comb_sm=(Code_meteo*10000)+Code_soil if
ArableArea<>"."&awc_ras_100<>"."&Code_meteo<>"."
drop awc_ras_100
drop csc_ras_100
drop gran_ras_100
drop perm_ras_100
drop Code_meteo
drop Arablearea
drop Code_soil
legend loadpal comb_sm 256_colors.pal
map comb_sm labels compass(90,8) ruler(4,95) saving(Comb_soil_met.bmp) 'pedoclim
areas 'map .bmp
export comb_sm saving(comb_sm) as(ArcGis)

collapse count(comb_sm) by(comb_sm) saving(Combinazioni) replace
save Xland.grp replace
save Xland.dct replace 'Xland.dct will be used in transport step

'Daily meteo data generation
use Combinazioni
drop if comb_sm="."
recast str comb_sm force
replace comb_sm="0"+comb_sm if len(comb_sm)=5
gen str2 Code_meteo=left(comb_sm,2)
recast int Code_meteo force
collapse count(Code_Meteo) by(Code_Meteo) saving(MeteodaGenerare) replace
save Combinazioni replace
use MeteodaGenerare 'MeteodaGenerare is a buffer file that will be deleted
gen Contatore=_i
merge Meteo.dct by(Code_Meteo)
save replace
scalar dimCell=%5% 'set grid cell dimension
use Combinazioni 'Combinazioni file will be used in crop simulation module
merge MeteodaGenerare by(Code_meteo)
replace Stazione=Stazione+"_gen.dct"
recast int comb_sm_c force
rename comb_sm_c Area replace Area=Area*(dimCell*dimCell) 'grid cell dimension
allows to 'calculate its area
drop Code_meteo
drop Code_Meteo_c
drop Contatore
drop X
drop Y
```

```
drop lat
drop Long
drop Alt
save replace
use Meteodagenerare
sum Contatore
scalar Max_Cont=_max
'Cycle to generate meteo data
cfor n=1 to Max_Cont: GeneraMeteo n %6% %10% 'Call to Climak in GeneraMeteo
'script
save MeteodaGenerare replace
erase MeteodaGenerare.dct

'------------------------- Crop simulation----------------------------
'Inputs:
'%2% crop
'%3% is kdw
'%4% is kdn
'%5% grid cell dimension

'Outputs:
'creates all the scenarios
'example scenario name: 01_1123_#Ma_50_50 where:
'01_1123=pedo-climatic areas
'#Ma=mais
'50 = Kdw*100
'50 = Kdn*100

scalar dimCell=%5% 'set grid cell dimension
'Soil parameter loading
use Code_soil.csv
recast int Code_soil force
save Code_soil.dct replace
use Combinazioni.dct
gen str4 Code_soil=right(comb_sm,4)
recast int Code_soil force merge Code_soil.dct by(Code_soil)
drop Code_soil
drop Awc_Class
drop CSC_Class
drop Texture_Class
drop Perm_Class
drop soil_code
merge CSSmini_SoilPar.dct by(SoilName)

'Crop parameter loading
gen str25 Code_Crop="%2%" 'crop choice
merge Code_crop.csv by(Code_Crop)
drop Code_Crop
merge CSSmini_cropPar.dct by(CropName)

'Set tolerated stress Kdw and Kdn
gen Kdw=%3%
gen Kdn=%4%
save Combinazioni.dct replace

'Scenario folders creation
string path=%6%+"\CreateScenarios_xland.EXE" ! %path% %6% %3% %4% 'call to an
executable that saves only the scenario folders in C:\Minicss\Scenario.

'2) Crop simulation
open %2%_%3%_%4%.csv '"%2%"_"%3%"_"%4%".csv is a buffer file that includes the
following 'columns: comb_sm, Resa_t_ha, Costi_euro_ha, Inagr_MJ_ha (namefile es.
mais_50_50.csv)
write "comb_sm","Resa_t_ha","Costi_euro_ha","Inagr_MJ_ha"
Lanciascenari 'Script that runs all the simulations
close %2%_%3%_%4%.csv '%2%"_"%3%"_"%4%".csv file now include the means for
Resa_t_ha, Costi_euro_ha, Inagr_MJ_ha for all the pedo-climatic combinations
```

```
'--------------Transport optimisation--------------------------------
'Minimum path calculus (cell-collecting centre)
'Two different transport phases: field(cell)-collecting centre, collecting-
processing centre

'Inputs:
'%6% working folder path
'%7% road graph file .dxf without extension and without blanks in name (e.g.
'Tracciati.dxf)
'%8% road junction file .csv without extension and without blanks in name (e.g.
'Intersezioni_Stradali.csv)
'%9% collecting centre coordinates file .txt or .csv (e.g. Consorzi2010.txt)
'%11% eventual obstacle file (e.g.Fiumi.fiu)

'Outputs:
'1) Xland_elab.csv file with columns:
'cell (Key)
'cell coordinates (X,Y)
'collecting centre to supply (Idconf)
'cell-collecting centre path length in m (Distanza_PC_m)
' cell-processing centre path length (Distanza_PT_m)
'transport costs in euro/ha (Cos_tra_PT_eu_ha)
'transport energy cost in MJ/ha (IntraPT_MJ_ha)

scalar dimCell=%5% 'set grid cell dimension
use Xland.dct clear
drop if comb_sm="."
gen ChiavePrim=_i
gen Code_bar=1
gen Area=dimCell*dimCell
gen Tipo_coltura=1
gen Codice_varieta=1
save Xland.csv replace

'Road geometry file conversion to .dat format -> Call to external executable
string path=%6%
! "%path%\PolyDXF2DAT.exe" "%path%\%7%.dxf"
'Road graph building -> Call to external executable
! "%path%\CostruisciGrafoStradale.exe" "%path%" "%8%.csv" "%9%.csv" "%7%.dat"
"170" 'Minimum path calculus -> Call to external executable
! "%path%\DistanzaDBparticella.exe" "%path%" "Grafo Stradale.gfs" "%9%.csv"
"%7%.str" "Xland.csv" "%11%.fiu"
'Return the Xland_Elab.csv file that includes for each cell:
'Idconf: code of the nearest collecting centre
'Distanza_PC_m : Distance cell-collecting centre
'Calculate minimum distance collecting-processing centre (Distanza_CT_m) -->
repeat previous procedure

use Xland_elab.csv clear
recast int Idconf force
merge DisCenTras.dct by(Idconf) 'DisCenTras = distance collecting-processing
centre file
'(temporary choice)
gen Distanza_CT_m=min(San_Giorgio_m,Cereal_Docks_m) 'choiche between two
processing plants (Distanza_CT_m)
drop San_Giorgio_m Cereal_Docks_m
'Transport cost coefficient (euro/t) selection
gen Coeff_PC_eu_t=0
replace Coeff_PC_eu_t=2.50 if Distanza_PC_m>0&Distanza_PC_m<11000
replace Coeff_PC_eu_t=2.70 if Distanza_PC_m>11000&Distanza_PC_m<16000
replace Coeff_PC_eu_t=2.90 if Distanza_PC_m>16000&Distanza_PC_m<21000
replace Coeff_PC_eu_t=3.20 if Distanza_PC_m>21000&Distanza_PC_m<26000
replace Coeff_PC_eu_t=3.50 if Distanza_PC_m>26000&Distanza_PC_m<31000
replace Coeff_PC_eu_t=3.60 if Distanza_PC_m>31000&Distanza_PC_m<36000
replace Coeff_PC_eu_t=3.80 if Distanza_PC_m>36000&Distanza_PC_m<41000
replace Coeff_PC_eu_t=3.90 if Distanza_PC_m>41000&Distanza_PC_m<46000
replace Coeff_PC_eu_t=4.10 if Distanza_PC_m>46000&Distanza_PC_m<51000
replace Coeff_PC_eu_t=4.30 if Distanza_PC_m>51000&Distanza_PC_m<56000
```

```
replace Coeff_PC_eu_t=4.50 if Distanza_PC_m>56000&Distanza_PC_m<61000
replace Coeff_PC_eu_t=4.80 if Distanza_PC_m>61000&Distanza_PC_m<66000
replace Coeff_PC_eu_t=5.00 if Distanza_PC_m>66000&Distanza_PC_m<71000
replace Coeff_PC_eu_t=5.30 if Distanza_PC_m>71000&Distanza_PC_m<76000
replace Coeff_PC_eu_t=5.50 if Distanza_PC_m>76000&Distanza_PC_m<81000
replace Coeff_PC_eu_t=5.80 if Distanza_PC_m>81000&Distanza_PC_m<86000
replace Coeff_PC_eu_t=6.30 if Distanza_PC_m>86000&Distanza_PC_m<91000
replace Coeff_PC_eu_t=6.50 if Distanza_PC_m>91000&Distanza_PC_m<96000
replace Coeff_PC_eu_t=6.80 if Distanza_PC_m>96000&Distanza_PC_m<100000
replace Coeff_PC_eu_t=(((Distanza_PC_m*1000)-100)*0.07)+6.80 if
Distanza_PC_m>100000
save Xland_elab.dct replace
'Transport cost(euro/ha) cell-collecting centre
'it uses the yield to calculate the transport cost per ha
use %2%_%3%_%4%.csv clear
recast int comb_sm force
save %2%_%3%_%4%.dct replace
use Xland_elab.dct clear
recast int comb_sm force merge %2%_%3%_%4%.dct by(comb_sm)'merge to main file
Xland.dct the yield (Resa_t_ha), agricultural costs (Costi_euro_ha) and energy
consumption (Inagr_MJ_ha)
gen Cos_tra_PC_eu_ha=Coeff_PC_eu_t*Resa_t_ha
gen Resa_tot_t=Resa_t_ha*((dimCell*dimCell)/10000)
collapse count(Chiaveprim) sum(Resa_tot_t) mean(Distanza_CT_m) by(Idconf)
saving(Conf_trasf.dct) replace

save Xland_elab replace
use Conf_trasf.dct clear
rename Chiaveprim_c ParXCenCof 'ParXCenCof is the number of cells for collecting
'centre
gen Coeff_CT_eu_t=0
replace Coeff_CT_eu_t=2.50 if Distanza_CT_m_a>0&Distanza_CT_m_a<11000
replace Coeff_CT_eu_t=2.70 if Distanza_CT_m_a>11000&Distanza_CT_m_a<16000
replace Coeff_CT_eu_t=2.90 if Distanza_CT_m_a>16000&Distanza_CT_m_a<21000
replace Coeff_CT_eu_t=3.20 if Distanza_CT_m_a>21000&Distanza_CT_m_a<26000
replace Coeff_CT_eu_t=3.50 if Distanza_CT_m_a>26000&Distanza_CT_m_a<31000
replace Coeff_CT_eu_t=3.60 if Distanza_CT_m_a>31000&Distanza_CT_m_a<36000
replace Coeff_CT_eu_t=3.80 if Distanza_CT_m_a>36000&Distanza_CT_m_a<41000
replace Coeff_CT_eu_t=3.90 if Distanza_CT_m_a>41000&Distanza_CT_m_a<46000
replace Coeff_CT_eu_t=4.10 if Distanza_CT_m_a>46000&Distanza_CT_m_a<51000
replace Coeff_CT_eu_t=4.30 if Distanza_CT_m_a>51000&Distanza_CT_m_a<56000
replace Coeff_CT_eu_t=4.50 if Distanza_CT_m_a>56000&Distanza_CT_m_a<61000
replace Coeff_CT_eu_t=4.80 if Distanza_CT_m_a>61000&Distanza_CT_m_a<66000
replace Coeff_CT_eu_t=5.00 if Distanza_CT_m_a>66000&Distanza_CT_m_a<71000
replace Coeff_CT_eu_t=5.30 if Distanza_CT_m_a>71000&Distanza_CT_m_a<76000
replace Coeff_CT_eu_t=5.50 if Distanza_CT_m_a>76000&Distanza_CT_m_a<81000
replace Coeff_CT_eu_t=5.80 if Distanza_CT_m_a>81000&Distanza_CT_m_a<86000
replace Coeff_CT_eu_t=6.30 if Distanza_CT_m_a>86000&Distanza_CT_m_a<91000
replace Coeff_CT_eu_t=6.50 if Distanza_CT_m_a>91000&Distanza_CT_m_a<96000
replace Coeff_CT_eu_t=6.80 if Distanza_CT_m_a>96000&Distanza_CT_m_a<100000
replace Coeff_CT_eu_t=(((Distanza_CT_m_a*1000)-100)*0.07)+6.80 if
Distanza_CT_m_a>100000
gen Cos_tra_CT_eu=Coeff_CT_eu_t*Resa_tot_t_t
gen IntraCT_MJ=(Distanza_CT_m_a/1000)*1.78*Resa_tot_t_t '1.78 MJ/tKm are
consumed by a tir>32 t during the transport (SimaPro with EcoInvent database)
recast int Idconf force
save replace
'Transport costs euro/ha for each cell
use Xland_elab.dct
merge Conf_trasf.dct by(Idconf)
gen CostraCTeupar=(Cos_tra_CT_eu/Resa_tot_t_t)*Resa_tot_t
gen Cos_tra_CT_eu_ha=CostraCTeupar/((dimCell*dimCell)/10000)
gen Cos_tra_PT_eu_ha=Cos_tra_PC_eu_ha+Cos_tra_CT_eu_ha
'Transport energy consumption MJ/ha for each cell
gen
IntraCT_MJ_ha=(IntraCT_MJ*(Resa_tot_t/Resa_tot_t_t))/((dimCell*dimCell)/10000)
gen IntraPC_MJ_ha=(Distanza_PC_m/1000)*5.27*Resa_t_ha '5.27 MJ/tKm are consumed
by a tractor and trailer during the transport (SimaPro with EcoInvent database)
```

```
gen IntraPT_MJ_ha=IntraPC_MJ_ha+IntraCT_MJ_ha
erase Conf_trasf.dct
'--------------------------------Conversione------------------------------
'Biomass conversion in a dry mill plant

'Inputs:
'Xland_elab.dct file

'Outputs:
'Xland_elab.dct file with columns:
'Biofuel yield (l/ha) (Biocarb_l_ha)
'Conversion costs in euro per ha (Cos_trasf_ha)
'By-product revenues in euro per ha (Ric_cop_ha)
'Conversion energy input in MJ per ha (Inpcon_MJ_ha)
'By-product energy in MJ per ha (Outcop_MJ_ha)
'Biofuel energy in MJ per ha (Outbio_MJ_ha)

'cif %2%="mais": Conversion 398 0.28 280 115 220 50 0
'cif %2%="soia": Conversion 160 0.07 0 0 0 0 0.01

'Conversion costs and revenues (Siemons et al., 2004)

gen Biocarb_l_ha=Resa_t_ha*398 'Biofuel yield: 398 l/t for maize, 400 l/t for
rapeseed, '160 l/t for soybean
gen Cos_trasf_ha=Biocarb_l_ha*0.28 'Conversion costs: 0.28 euro/l for
bioethanol, 0.07 euro/l for biodiesel

'Maize
gen Ric_DDGS_ha=((Resa_t_ha*280)/1000)*115 'By-product revenue (1): 280 kg DDGS
per t 'maize, sold at 115 euro/t
gen Ric_CO2_ha=((Resa_t_ha*220)/1000)*50 'By-product revenue (2): 220 kg CO2 per
t maize, 'sold at 50 euro/t

'Soybean
'gen Ric_cop_soia_ha=Biocarb_l_ha*0.01 'By-product revenue 0.01 euro/l

gen Ric_cop_ha=Ric_DDGS_ha+Ric_CO2_ha
'gen Ric_cop_ha=Ric_cop_soia_ha

'Conversion energy (Hill et al., 2006)
'Maize
'1) Inputs:
gen Inpcon_MJ_ha=Biocarb_l_ha*12.73

'2) Outputs:
gen Outcop_MJ_ha=Biocarb_l_ha*4.31
gen Outbio_MJ_ha=Biocarb_l_ha*21.26

'Soybean
'gen Inpcon_MJ_ha=Biocarb_l_ha*8.08
'gen Outcop_MJ_ha=Biocarb_l_ha*21.94
'gen Outbio_MJ_ha=Biocarb_l_ha*32.93

'-----------------------AGRO-ENERGY CHAIN BALANCE------------------------------
-
'ECONOMIC BALANCE
'Inputs:
'agricultural costs per ha Costi_euro_ha
'transport costs per ha Cos_tra_PT_eu_ha
'conversion costs per ha Cos_trasf_ha
'byproduct revenues per ha Ric_cop_ha
'biofuel yield per ha Biocarb_l_ha

'Calculation:
'Economic balance equation:
'Costs(euro/ha) - by-product value (euro/ha) = Biofuel yield (litri/ha) *
Threshold price ' (euro/litro)
gen PrezzoEq_eu_l=(Costi_euro_ha+Cos_tra_PT_eu_ha+Cos_trasf_ha-
```

```
Ric_cop_ha)/Biocarb_l_ha

'ENERGY BALANCE
'Inputs:
'agricultural energy input per ha Inagr_MJ_ha
'transport energy input per ha IntraPT_MJ_ha
'conversion energy input per ha Inpcon_MJ_ha
'by product energy per ha Outcop_MJ_ha
'biofuel energy per ha Outbio_MJ_ha
'Calculation:
'Energy ratio fossil energy input/renewable energy output
gen
Energy_ratio=((Inagr_MJ_ha+IntraPT_MJ_ha+Inpcon_MJ_ha)/(Outbio_MJ_ha+Outcop_MJ_ha))*100
'Energy balance equation:
'biofuel energy + by-product en -(agri energy + transp energy + conver energy)
gen BilEner_GJ_ha=(Outbio_MJ_ha+Outcop_MJ_ha-
(Inagr_MJ_ha+IntraPT_MJ_ha+Inpcon_MJ_ha))/1000
save Xland_elab.dct replace
script end
```

# Annex IV

## Basic SemGrid Commands

Fabrizio Ginaldi

# Basic SemGrid commands

| Task | Command | Description |
|---|---|---|
| **General** | `about` | copyright information |
| | `dir` | display the files in the current directory |
| | `exit` | exit the program |
| | `set` | set up the modelling environment |
| **Grids** | `camc` | Cellular automata-Markov chain simulation (new) |
| | `export` | exports current grid layers in different formats |
| | `import` | imports to the current project, grids of different formats |
| | `map` | generates a map of a grid layer |
| | `overlay` | overlays different layers |
| | `resize` | resizes (clip or enlarge) the area of a grid project |
| | `insert` | inserts georeferenced points into current grid |
| | `distance` | creates a layer with minimum distance values |
| | `harvest` | generate layers with sum/mean of cells in neighbourhood |
| | `spread` | spread XY table data on grid layers (new) |
| | `spatial` | data spatialization (IDW,Voronoi) |
| | `sunh` | potential sunshine hours for grid cells with hillshading (new) |
| **File management** | `append` | add a dataset (by rows) |
| | `close` | close the open text file |
| | `collapse` | generate a dataset with statistics from the current |
| | `erase` | eliminate files from model and working directory |
| | `merge` | add a dataset (by columns) |
| | `open` | open a text file for text output |
| | `save` | save the current dataset |
| | `substitute` | string substitution (also regular expressions) in files |
| | `use` | load a new file |
| | `write` | write a line of text in the open file |
| **Data display** | `describe` | list variables and information of current dataset |
| | `header` | list, modifies and inserts header items and labels |
| | `list` | list values of variables |
| | `listc` | list values of variables, by column (1 obs per time) |
| **Data management** | `class` | create a code variable from a continuous variable |
| | `decode` | decode code and legend into categorical variable |
| | `drop` | erase variables/observation from current dataset |
| | `fgen` | fast generation of unary an binary operations |
| | `generate` | calculate new variables from math expressions |
| | `keep` | keep variables/observation of current dataset |
| | `legend` | display and modifies legends (codes, colour, labels) |
| | `recode` | recode the values of a code variable |
| | `rename` | change the name of variables |
| | `replace` | Re-calculate variables (columns) or observ. (rows) |
| **Variables** | `matrix` | manage matrix ambient variables |
| | `scalar` | manage scalar (numerical) ambient variables |
| | `string` | manage string ambient variables |
| **Statistics** | `correlate` | correlation coefficients among variables |
| | `cumulate` | calculate empirical cumulated distributions |
| | `rank` | generate a variable with the statistical rank |
| | `summarize` | descriptive statistics (mean, standard dev., min., max.) |

| | | |
|---|---|---|
| | **`table`** | create statistical tables from current variables |
| **Utilities** | **`by`** | repeat commands for by groups |
| | **`cfor`** | super-command to repeat SEMoLa commands |
| | **`cif`** | super-command for conditional execution of commands |
| | **`markest`** | estimate MC probability transition matrix among states |
| | **`marksim`** | Markov chain simulation |
| **help** | **`help`** | Command help |

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