Alma Mater Studiorum – Università di Bologna

DOTTORATO DI RICERCA IN

Colture Erbacee, Genetica Agraria, Sistemi Agroterritoriali

Ciclo XXIII

Settore Concorsuale di afferenza: 07/B1 – Agronomia e Sistemi Colturali Erbacei ed Ortofloricoli

Settore Scientifico disciplinare: AGR/02 – Agronomia e Coltivazioni Erbacee

TITOLO TESI

LCA-GIS INTEGRATED APPROACH FOR A SUSTAINABLE LAND USE UNDER ENERGY CROPS

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Esame finale anno 2012

To my family

Nicola Di Virgilio

LCA-GIS INTEGRATED APPROACH FOR A SUSTAINABLE LAND USE UNDER ENERGY CROPS.

PhD Thesis on Herbaceous Crops, Breeding, Agro-environmental systems. XXIII Ciclo, University of Bologna, ITALY.

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Abstract ENGL

Di Virgilio N., 2012. **LCA-GIS integrated approach for a sustainable land use under energy crops.** Doctoral Thesis, University of Bologna, Italy.

Usually, when dealing with land suitability studies for crops, only environmental pedo-climatic factors are used. Crop production chain also means impact due to agronomic practices and the environment can be sensible to them basing on the site-specific vulnerability. This study wanted to define a method to spatially relate crop impacts to the environment and then to include it in land suitability procedures. LCA was used to estimate impact indicators of few herbaceous food and energy crops, and were combined with vulnerability maps defined using GIS, through the calculation of "allocation risk" values for each crop-vulnerable land combination. Energy crops were considered as an alternative land use to potentially increase the environmental sustainability. The case-study showed that crop allocation to minimize environmental risks may change basing on considered impact indicators. Methods for merging several impacts in one map were also defined. Results were as optimal crop land allocation maps combining several crops compared with conventional cropping systems, e.g. maize/wheat rotation: crops with higher impacts can be allocated in lower vulnerable lands, and vice versa. If impact risk is a priority, maize, rapeseed, wheat, sunflower and fibre sorghum should be grown only in low or moderate vulnerable lands, while perennial grasses can be grown in all areas, thus representing a possible solution to increase the sustainability of the rural land use.
Developed LCA-GIS approach represents an innovative and useful decision support systems (DSS) for minimizing impacts for the environment when allocating crops. Also it represented a useful tool for understanding the sustainability of current land use by integrating it with crop statistics and land use maps.

Keywords: Geographic information system (GIS), Life cycle assessment (LCA), Energy crops, Food crops, Wheat, Maize, Sunflower, Rapeseed, Fibre sorghum, Arundo donax, Cardoon, Switchgrass, Land use, Environmental impact, Sustainable agriculture.

Abstract ITA

Di Virgilio N., 2012. **Approccio integrato LCA-GIS per un uso sostenibile del suolo con le colture energetiche.** Tesi di Dottorato, Università di Bologna, Italia.

In genere, negli studi di vocazionalità delle colture, vengono presi in considerazione solo variabili ambientali pedo-climatiche. La coltivazione di una coltura comporta anche un impatto ambientale derivante dalle pratiche agronomiche ed il territorio può essere più o meno sensibile a questi impatti in base alla sua vulnerabilità. In questo studio si vuole sviluppare una metodologia per relazionare spazialmente l'impatto delle colture con le caratteristiche sito specifiche del territorio in modo da considerare anche questo aspetto nell'allocazione negli studi di vocazionalità. LCA è stato utilizzato per quantificare diversi impatti di alcune colture erbacee alimentari e da energia, relazionati a mappe di vulnerabilità costruite con l'utilizzo di GIS, attraverso il calcolo di coefficienti di rischio di allocazione per ogni combinazione coltura-area vulnerabile. Le colture energetiche sono state considerate come un uso alternativo del suolo per diminuire l'impatto ambientale. Il caso studio ha mostrato che l'allocazione delle colture può essere diversa in base al tipo e al numero di impatti considerati. Il risultato sono delle mappe in cui sono riportate le distribuzioni ottimali delle colture al fine di minimizzare gli impatti, rispetto a mais e grano, due colture alimentari importanti nell'area di studio. Le colture con l'impatto più alto dovrebbero essere coltivate nelle aree a vulnerabilità bassa, e viceversa. Se il rischio ambientale è la priorità, mais, colza, grano, girasole, e sorgo da fibra dovrebbero essere coltivate solo nelle aree a vulnerabilità bassa o moderata, mentre, le colture energetiche erbacee perenni, come il panico, potrebbero essere coltivate anche nelle aree a vulnerabilità alta, rappresentando cosi una opportunità per aumentare la sostenibilità di uso del suolo rurale. Lo strumento LCA-GIS inoltre, integrato con mappe di uso attuale del suolo, può aiutare a valutarne il suo grado di sostenibilità ambientale.

Parole chiave: Sistemi Informativi Territoriali (SIT), Ciclo di Vita dei Prodotti (LCA), colture energetiche, colture alimentari, grano, mais, girasole, colza, sorgo da fibra, canna comune, cardo, panico, uso del suolo, impatto ambientale, agricoltura sostenibile.

Preface and Acknowledgements

The topic of this thesis came in the framework of a project where the selection of high potential yield crops for energy end-use and their relation with the environment were among main targets. The study of the energy balance was of course almost foregone, as well as the assessment of the CO_2 emissions in order to define opportunities of reductions. The Life Cycle Assessment approach was followed to study several selected dedicated biomass crops, that means to quantify input and output of the entire biomass production chain. Under this framework, with the support of commercial databases and software, the possibility to understand an overall impact of agro-energy chains is easily obtainable. This aspect is anyway very important in the case of biomass crops, because in parallel with the high yield capacity, a general sustainability is also required. Sustainability refers to several aspects of a production chain, as economy, sociology and environment. If from one side to select best energy crops also considering their overall impact to the environment is important, the forward step is to try to imagine how these impacts act on the environment, also because ones defined a more or less novel biomass production chain, this last will be grown in a land portion where site-specific conditions may influence, together yield potentials and agronomic strategies, also the crop impact level to the environment itself. The topic of this work was thus to develop a method to link the environmental impact of an agro-energy chain to site-specific characteristics of the land where they are on going to be located, under a planning strategy that wants to minimize the impact for the environment.

Questions erased: What’s the effect of the evaluated LCA impact of a crop on a territory when one of crop is really there cultivated? How the site-specific condition could act on the impact levels of crop production chains?

In fact, the idea moved to a more general approach, i.e. crop production chains in general and not only energy crops, and energy crops were considered as an alternative land use potentially representing a tool for increasing land sustainability.

We wanted this method to be easy to understand, fast and basing of broadly used tools, thus the LCA procedures, well know and standardized by ISO, and GIS were integrated and acting as DSS in order to implement insights to increase the sustainability of the crop allocation in the rural area.

This PhD was mainly carried out at the Institute of Biometeorology of the National Research Council of Italy (CNR-IBIMET) and at the Department of Agroenvironmental Science and Technology (DiSTA) of the University of Bologna. Part of the PhD program was done at the “Facultade de Ciències e Technologia - Universidade Nova de Lisboa (Portugal) (May 2009), under the application of a Short Term Scientific Mission of the COST Action 734 - Impact of Climate Change and Variability on European Agriculture: CLIVAGRI. In October 2009, at NIWA (National Institute of Water & Atmospheric Research), Auckland (New Zealand) in the framework of a program for the international collaboration in research of the National Research Council of Italy. In the period August-September 2011, at the Alterra Institute of the Wageningen University and Research (The Netherlands).

I would like thus to thank all above mentioned Institutions in the person of my tutor Andrea Monti, Federica Rossi, Ana Luisa Fernando, Rilke De Vos, Berien Elbersen and Igor Staritsky.

A particular thank to Ezio Battistel of the Institute Eni - G. Donegani, Via Fauser 4 - 28100 Novara (IT) for constructive feedbacks and Simone Fazio for providing LCA results of crops.

The present thesis has been supported by Eni S.p.A. within the Project “Network: crops for energy, and carbon recycling”.

Bologna, 5/04/2012.

Nicola Di Virgilio

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ABBREVIATIONS

AMCM. Additive method of classified maps.

CF. Characterization factors.

CMM. Composed multiplicative method.

EU. Eutrophication

FWT. Freshwater toxicity

GIS. Geographic Information Systems.

HUMT. Human toxicity

LCA. Life Cycle Assessment.

LCI. Life Cycle Inventory.

LCIA. Life cycle impact assessment.

LVM. Land vulnerability map.

SAM. simple additive method.

TUA. Total Agricultural Area.

UUA. Utilized Agricultural Area.

1. **General introduction**

Introduction to the study

Aims and scope

Overall structure of the thesis

Introduction to the study

Land is a resource that is used by humans to satisfy their needs: food, house, production of manufactures, recreation, transportation, energy, and so on. It must be stressed that it is a limited resource, both in term of space than in term of his ability to ensure functions and his state of health is strictly related to human wellbeing. This easily means that sustainability is an important concept to deal with when organizing the use of the territory, and of course also to be applied to agriculture, one of the main sector directly, and more that the others, mutually connected with the soil. Moreover, limitations to a sustainable use of rural areas also comes from competition among the several needs that must be satisfied by the agricultural sector (fibre, feed, food, fuel). For example the increasing demand of biofuels coming from EU, where the demand for energy crops is stimulated with the setting of targets, more than 50% of the renewable energy consumption should come from biomass, including crops. It is acknowledged that satisfying these targets could bring substantial sustainability risks particularly connected with the competition with food and with intensification practices of existing crops. Scientific community and governments are studying sustainability criteria for bioenergy developments, identifying few constraints. When dealing with land allocation, sustainability criteria prohibits e.g. conversion of natural ecosystems for biofuels production (Article 17 of the EC Directive on the promotion of the use of energy from renewable sources) or suggests the use of agricultural marginal lands.

All crops socio-economic functions, and also their land use efficiency, are strictly related with the territory and with the site-specific variability of main factors (climate, soil fertility, morphology, etc.). These can affect yields, agronomic practices, farmer’s income, input levels, use of fossil fuels, and so on. The study of the territory in its overall complexity, of available resources, site-specific conditions, current land use schemes, is a precondition to support the sustainability of the land use of rural areas, defining the place where crop can accomplish the best potential functions. Finding the place where most conditions are favourable brings to the land suitability concepts, which the main product is the land suitability map. In this map the propensity of a territory to host production chain is indicated basing on several land parameters, the higher the number of involved land characteristics, the higher the reliability. It means to find the best place for the best agro-chain, or, in other words, best environmental conditions for a given crop, thus representing a Decision Supporting Tool for sustainable choices. As also stressed in the next chapters, even if approaching with a multivariable procedure, it considers only the effect of the environment (in terms of temperatures, rainfalls, growing degree days, latitude, etc.) to crop chains. Not much can be found about environmental impact, another important aspect linked with the land use sustainability. A crop production chain intrinsically contains an impact for the environment linked to agronomic practises. Some studies reports that the agronomic phase, is the most impacting step in the food chain production, mainly due to the use of the recourses and of the soil ((Brentrup, Küsters et al.

2000); (Brentrup 2003)). There is a growing general awareness and consensus among politicians and farmers on the need to reduce the environmental loads, optimization of agronomic inputs (e.g. fertilizers, etc.) and natural resources, primarily water. These impacts are different, based on site-specific conditions, not only because the availability of resources can be different, but also depending by the different environmental sensibility to the impacts. Thus, the main idea of this study is to consider the environmental impact of crops in their allocation when dealing with land suitability studies, and not only the effect of environment to crop production chains.

Life Cycle Assessment (LCA) procedures, which main definitions are described in the next chapters, is a useful and standardized tool for assessing several categories of impacts of crop production chains toward main environmental compartments, while the land site-specific sensibility (vulnerability) to those impacts can be defined with the support of Geographical Information Systems (GIS). Agriculture anyway is expected to be environmentally benign, as expressed in the “Directions towards sustainable agriculture of the Commission of the European Communities” (Communities 1999). The integration of these two tools give the possibility to increase the environmental sustainability of crop allocation (land use in rural areas): simply, where the environment shows high vulnerability, only crops with a low impact would be advisable.

This approach will be applied in the current study to maize and wheat, two traditional cash crops, and to some herbaceous dedicated energy crops, seen in this study as alternative land uses for which their potential integration in the traditional rotation may represent a tool for increasing the sustainability of the land use under a planning strategy. To energy crops several environmental benefits have been recognised, described in the next chapters. Among all, this study focalized on herbaceous energy crops or with dual purpose (sunflower, rapeseed, fibre sorghum, cynara, giant reed, miscanthus, switchgrass), for their possibility to be compared with two main land use herbaceous food crops, as wheat and maize.

The result of this approach would give indication on which locations are less vulnerable to impacts, locate crops with higher impacts in less vulnerable areas, and thus increasing the sustainability from the environmental point of view. Maps of most suitable areas with a multivariate approach considering the socio-economic, pedoclimatic and environmental impact will represent a decision support system for land actors with attention to emission reduction, energy efficiency, economic returns and also to environmental impacts.

Aims and scope

Main scope of this work is thus to define a method to link the impact of crop production chains with the site-specific vulnerability of the territory and using it in the allocation of crops. The tentative will include the following main tasks:

- Definition of crop impacts with the use of LCA procedure
- Impacts result comparison among food and no-food crop
- Defining impact categories able to describe local impacts
- Definition of the vulnerability of the territory with the use of GIS
- Methods for the use of multiple LCA impact indicators
- Link between the LCA impacts with the vulnerability levels of the environment
- Optimal crop allocation for the minimization of the environmental impact
- Sustainability assessment of current land use and the role of energy crops in increasing environmental sustainability

Overall structure of the thesis

First part of the thesis focuses on describing the principles behind the definition of the method to link impact to the vulnerability. A description of what LCA means and how it can be used in this study is outlined, as well as how GIS can support land analysis and the production of vulnerability maps to be related with crop impacts. It is explained the concept behind the calculation of crop allocation risk values and how they are used in allocating crops in order to minimize the environmental impacts.

In the second part of the thesis these principles are applied to a case study in order to bring out critical aspects, possible implications and way of improvements, these last also coming out in the last part of the thesis, where few prospects in applications are mentioned.

2. Baseline principles

Energy crops as alternative land uses

Life Cycle Assessment for crop production chains

Land suitability for energy crops and the role of Geographic Information Systems (GIS)

A novel concept of optimal land allocation: from 'environment-to-crop' toward 'crop-to-environment" approach

Site specific impacts and definition of land vulnerability maps

Integration between LCA and land vulnerability

Use of multiple impact indicators to optimize crop allocation

Highlights

Herbaceous energy crops ensure few socio-environmental benefits and they are ready to be introduced in the traditional land use of rural areas.

Even if land suitability studies use multivariate procedures and models, generally the site-specific environmental impact of crop production chains appraisable with LCA is not considered, but it can increase the environmental sustainability of crop allocation, maximized if considering as many as possible LCA impact indicators with local effect, following the calculation of crop allocation risks. Land vulnerability maps are the link between impacts and site-specific land characteristics. The use of multiple impact indicators brings to the need of defining integration methods for impacts and land vulnerability maps.

Energy crops as alternative land uses

Although the approach in land suitability proposed in this study can be potentially applied to agro-production systems in general, in this thesis a particular attention is toward energy crops. One of the main task of the method under development is to optimize the environmental sustainability of the land use in agricultural areas. Dedicated energy crops are considered as an alternative land use able to decrease environmental burdens of land use in specific vulnerable locations, being part of more general tools i.e. conservative practices, intercropping, agro-forestry, etc. (see also www.fao.org/nr/land/en/ or (Dumanski, Peiretti et al. 2006)). Dedicated energy crops are crops that are grown for energy production, their main product is the energy, in the form of biofuels, or combusted for its energy content to generate electricity or heat. Lot of literature is already available, classifying them in woody or herbaceous, mainly producing lignocellulosic material or more simple carbohydrates, being annual or perennials or oil crops from which seed the bio-diesel may be extracted, etc. ((Zegada-Lizarazu and Monti 2011); (Hodsman, Smallwood et al. 2005); (El Bassam 1998); (El Bassam 1998); (Lastrico, Arnone et al. 1990)). Among all, this study focalized on herbaceous crops, for energy or with dual purpose (sunflower, rapeseed, fibre sorghum, cynara, giant reed, miscanthus, switchgrass), mainly for their possibility to be compared with two main land use involving herbaceous food crop, as wheat and maize, and thus focalizing in sowable land portion.

Main agronomic and physiological characteristics of most promising energy crops as switchgrass (*Pannicum virgatum*), miscanthus

(*Miscanthus spp.*), giant reed (*Arundo donax*) and cynara (*Cynara cardunculus*) ((Monti, Venturi et al. 2001); (Monti and Zatta 2009); (Cosentino, Copani et al. 2006); (Cosentino, Patane et al. 2007)), rapeseed for oil production (Baux, Colbach et al. 2011), sunflower oil quality (Yin, Ma et al. 2012), fibre sorghum, etc., have been studied in Europe and in most of the case the acquired knowledge is enough to allow those novel crops be cultivated by farmers and introduced in the traditional land use ((Zegada-Lizarazu, Elbersen et al. 2010); (El Bassam 1998); (Zegada-Lizarazu and Monti 2011)).

In general, biomass crops are recognized to provide significant environmental benefits that depend on species, crop management, but also to land allocation, scale level and environmental characteristics (Tilman, Hill et al. 2006). In the following table, elaborated by (Sims, Hastings et al. 2006), the main benefits which make energy crops attractive are reported. Main interest is linked to their high yield potential, the high contents of lignin, cellulose and hemicelluloses, low inputs and their positive social and environmental benefits (tables 2.1).

In particular, there is a growing general awareness and consensus among politicians and farmers on the need to reduce the environmental loads, optimization of agronomic inputs (e.g. fertilizers, etc.) and natural resources, primarily water. Examples of very positive effects by the cultivation of energy crops have been reported on nitrogen leaching, water quality and biodiversity for example in miscanthus ((Lewandowski and Heinz 2003); (Semere and Slater 2007)) and for switchgrass, this last also exceeding carbon sequestration rates in the soil of 20-30 times those of annual crops ((Samson, Mani et al. 2005); (McLaughlin and Walsh 1998)).

Table 2.1. Main benefits of biomass crops (from: (Sims, Hastings et al. 2006)).

Environmental benefits	Socio-Economic benefits
Low requirement in water, fertilizers and chemicals;	development of new markets (e.g. biofuels and bio products);
reduction of soil degradation and erosion in the case of perennials	new sources of income and employment in rural areas;
low GHG emissions;	biodiversity increase;
phytoremediation capacity;	potential inland renewable energy sources (> self energy production);
adaptability to marginal lands;	new educational oppurtunity for farmer for new managing stategies.
natural habits for wildlife.	

Again, in the case of switchgrass, benefits were assessed also on soil quality, recovery function of wildlife species (McLaughlin and Walsh 1998). In particular for perennial grasses among energy crops, as miscanthus or switchgrass, benefits are in fact even more evident. Compared to traditional row annual crops, perennial crops generally require lower energy inputs (fertilizers, pesticides etc.), can be grown on marginal cropland and provide benefits in terms of soil structure and stability (e.g. reduce soil loss, erosion and runoff), soil quality (as increase organic matter and nutrient retention) and biodiversity (e.g. shelter for autochthonous wildlife species), surviving over prolonged dry periods, acting as carbon sinks and filter systems for removing agrochemicals from water before these pollutants reach surface or groundwater bodies. Another aspect is linked with the phytoremediation (Lord, Atkinson et al. 2008) or irrigated production with waste water, sludges (Nielsen 1994) or slurry (Gericke, Bornemann et al. 2012), with which the cultivation of energy crops can be possible.

Selected high-yielding energy crops, producing high amount of vegetal biomass, can also be an important source of biomass feedstock for bio-based products and renewable energy, with the development of new and profitable markets for rural areas (biofuels, fine chemicals, bio-materials, etc.). Lignocellulosic biomass can be converted into energy by several processes along with several by-products with high added values: consumers are increasingly looking for ‘green’ or bio-based products.

Ultimately, it can be assumed that energy crops can provide important environmental benefits, thus to be considered as a possible tool in optimizing the sustainability of the rural land use, but, at the same time, also they can potentially represent an alternative source of income and employment for farmers, which would became the feedstock providers for an advanced bio-indudry of the future.

Life Cycle Assessment for crop production chains

The environmental impact is a vague concept that includes such diverse areas as health, water pollution, soil erosion, biodiversity, CO_2, etc. The quantification of all these aspects is quite a complicated issue. An help can come by the LCA (Life Cycle Assessment). LCA, also called ecobalancing, is a standard tool to assess all environmental impacts associated with a product, process or activity by accounting and evaluating the resource consumption and the emissions. The methodology of LCA has been developed to define insight in the environmental effects of products during the whole life cycle or process chain (from cradle to grave), with the quantification of the impact with the use of several impact categories, or indicators. LCA is generally accepted as a method to compare the impact of products that are used for the same purpose. The standard procedure is defined by ISO 14040-43 (Standardization 1997). The LCA standard procedure contains the following steps: 1) **Goal and scope definition**, where the goal, available means defining the depth and the width of the analysis, are defined. In relation to the goal, a functional unit is chosen, that for crop production system can be hectares or mass unit of the product. The functional unit is the entity in which all impact criteria are expressed. 2) **Life cycle inventory** (LCI), where all recourses used and emissions produced which causes ecological effect are accounted. 3) **Life cycle impact assessment** (LCIA), where all different substances are translated to a score on certain environmental categories. The inventory data are multiplied by characterization factors (CF) to give indicators for the environmental impact categories. The characterization factors represent the potential of a single emission or resource consumption to contribute to the respective impact category (Brentrup, Kusters et al. 2004). An example for such an impact category, or indicator, is the global warming potential (GWP) expressed in CO_2-equivalents, which is derived from the rate of CO_2, CH_4, N_2O and CFC emissions multiplied by their respective characterization factor (e.g. 1 for CO_2, 310 for N_2O). According to ISO the aggregation of inventory results to impact categories is mandatory in LCIA (ISO 2000). There could be several indicators that aggregates different substances. They also depend on the chosen impact method. One, as an example, among the most used in particular in the agricultural sector, is the CML2 baseline 2000 (Institute of Environmental sciences, Leiden University, NL) which involves the following categories: abiotic depletion, global warming potential, ozone layer depletion, human toxicity, freshwater toxicity, marine water toxicity, eutrophication, and others. 4) **Normalization**, which means giving insight into the seriousness of the score on that specific environmental category, comparing the score impact due to the life cycle of the product and the total score on that environment for example in the country or region during a year. The result of the classification step is the “environmental profile”. The resulting normalized indicator values give the share of the analyzed system in the defined reference, e.g. European values for the respective impact categories. For a production system under investigation, this would mean the division of the Global Warming Potential calculated for the system by the total Global Warming Potential for a defined region, e.g. Europe (Brentrup, Kusters et al. 2004). 5) **Evaluation**. The environmental impact of the product can be valued, usually done qualitatively, by valuing and discussing the separate scores of the environmental profile in a multi-criteria analysis. Valuation can also be done quantitatively, by attaching a weighing factor to each environmental category. The normalized indicator values can be multiplied by weighting factors, which represent the potential of the different environmental impact categories to harm three main terrestrial themes: natural ecosystems, human health and resources. For example the normalized indicator value for global warming for a production system under analysis is multiplied by a specific weighting factor for global warming. Subsequently, the weighted indicator values can be summed up to one overall environmental indicator (Brentrup, Kusters et al. 2004). These two last operations are optional element of the LCIA. 6) **Improvement analysis**, a step to identify areas of possible improvement (Biewinga and Van der Bijl 1996).

The LCA method was elaborated for the analysis of industrial products, but several studies adapted this approach also to agro-production chains (Brentrup, Kusters et al. 2002). Application to agricultural sector raised several problems: the boundary between production system and environmental system is much more difficult to define, especially because the soil can be as part of both; several environmental indicators that are important in agriculture have to be added, such as effects on erosion and groundwater depletion; the contribution of agriculture to natural and landscape added value is hard to quantify with LCA; land use, that can be a minor aspect for most industrial systems, it is dominant for agricultural production (Biewinga and Van der Bijl 1996).

Agriculture anyway is expected to be environmentally benign, as expressed in the Directions towards sustainable agriculture of the Commission of the European Communities (Communities 1999). To evaluate the sustainability of agricultural production systems, it is necessary to have appropriate indicators and the answer can anyway come from LCA. In fact, agricultural production systems contribute to a wide range of environmental impacts (e.g. climate change, acidification, eutrophication etc.). The analysis of individual effects does not permit an overall conclusion from an environmental point of view on the overall preference of one or another production strategy (Brentrup 2003). The LCA procedure is in line with a multi-criteria evaluation and gives this possibility to quantify and also synthesize several aspects related to the environmental impact also for the agricultural sector. The LCA was established to investigate all environmental impacts related to an entire production process (Consoli, Allen et al. 1993), then using this methodology does not only determine the impacts from the field cultivation step, but also all impacts related to the implementation of production factors, such as emissions and resource consumption due to the production of fertilizers, chemicals, machinery, and so on. All impacts are related to one common unit (e.g. 1 ton of grain or 1 hectare) and summarized into environmental effects (such as climate change or acidification), directly related to the management of the production chain, or even aggregate them into a unique environmental index. Such an index allows the ranking of different crop production chains or alternative management according to their overall environmental performance. In particular when dealing with agricultural chains, also the impact assessment procedure, the aggregation methods for the different impact categories and the final calculation of a summarizing environmental index, are still in debate, as well as the missing integration of important impacts relevant to agriculture, e.g. land use, resource consumption (Brentrup, Kusters et al. 2001). Details on aspects concerning the application of the LCA procedure to agricultural crop production chains with few crops case studies and specific impact indicators can be found in the Brentrup's. studies ((Brentrup, Kusters et al. 2001); (Brentrup 2003); (Brentrup, Kusters et al. 2004); (Brentrup, Kusters et al. 2004)).

Crops have different agronomic practices and the environmental impacts also will be equally different, more or less relevant also depending on site-specific conditions (Brentrup, Kusters et al. 2004). Some cultures, for example, can represent a danger to the health of the waters, others to human health, etc., these depending for example by the use of chemicals in the applied crop management. Furthermore, the evaluation of environmental effects in LCA is not specific for a certain location. Especially concerning agriculture, the meaning of several environmental effects may be very much dependent on site-specific situations. For example in the case of the aquatic ecotoxicity (different between oceans and inland waters), acidification (effects depend on distribution and sensitivity of areas), or ground water depletion (water is not scarce everywhere) (Biewinga and Van der Bijl 1996). Ultimately, the environmental impact is an indicator in itself insufficient to translate the environmental risk associated with the crop, and therefore must be contextualized and commensurate to an environmental reference. This aspect is still under debate among LCA experts.

LCA anyway represents a useful tool for the evaluation of the environmental burden. Beside the standard procedure that makes it valuable for comparisons, also several software managing databases and tools are now available giving the possibility to carry out relatively reliable LCA analysis very quickly. Several studies moreover applied it on crop production chains, adjusting several uncertain aspect related to the application of this method to crop production chains. In particular in Netherlands, three institutes (Centre for Agriculture and Environment (CLM), Centre for Environmental studies (CML) and Agricultural Economic Institute (LEI)) are working in elaborating specific LCA procedure for agriculture.

Impact indicators are not linked with site-specific conditions, at least at a first stage of the LCA analysis. This means that the evaluation of the environmental impact of a crop production chain may be done independently by the characteristics of the territory where it will be located. Ones defined the impact using several indicators as descriptors, these lasts may be related with the vulnerability of the environment where the production chain is located, and thus to adjust the crop impacts. This link is the key aspect of this study and it will be of course explored in the following paragraphs.

Land suitability for energy crops and the role of Geographic Information Systems (GIS)

There is a strict relation between crop cultivation and the site-specificities of the territory. Same production chains located in different environments can give different results in term of yield production, incomes for farmers, cost efficiency, economic sustainability, etc. Of course this is also valid for energy crops, short rotation forestry or herbaceous, annual or perennials, greatly vary in yields, pedoclimatic needs, agronomic managements, shape, quality of biomass for the energy conversion. In general, their yield potential strictly depend on their capacity to adapt to site-specific pedoclimatic conditions. Moreover, the overall outcome of a novel agro-energy chain, which have to find a space in the current land use, may depend on the site-specific socio-economic context, namely for example as know-how availability, the possibility to find a market and infrastructures as a suitable mechanization and storage plants, the inclination of local public offices and of the public opinion to recognise their added values of environmental payback of agro-energy chains and then to stimulate their introduction in the neighbourhood. Another important aspect is to consider the possibility to develop a complete energy production chain, from raw material production to energy end use, within a restricted area, at local level. This may help to reduce GHG emissions and costs of transports, help local rural economy and the energy autonomy.

All these aspects, even if maybe at different scale levels, are site-specific dependent. The study of the territory in its overall complexity is then a precondition in order to maximize benefits from the introduction of agro-energy chains. Finding the place where major conditions are favourable brings to the land suitability concept, which the main product is the **land suitability map**. In this map the propensity of a territory to host a novel crop chain is reported, basing on several land parameters (pedo-climatic, agronomic, socio-economic). The higher the number of involved land characteristics, the higher the benefits and returns coming from the crop. The suitability maps show area where environmental characteristics are able to satisfy crop requirements and show conditions for an optimal and sustainable development of the production chain. It means to find the best environmental conditions for a given crop. From this point of view, this approach is a mono-direction approach we could call “**environment-to-crop**” oriented approach. An example of land suitability map is reported in fig. 2.1., where land allocation of some perennial energy crops in Europe, proposed by (Zegada-Lizarazu, Elbersen et al. 2010) and (Krasuska, Cadorniga et al. 2010) is reported (fig. 2.1). The map indicate the climatic feasibility according to crop requirements, thus following an environment-to-crop oriented approach.

The capacity to analyse the environment, understand all factors that characterize it, is a precognition to carry out a land suitability study, and main tools are represented by Geographic Information System, better known as GIS. GIS is a tools system designed to capture, extract, store, manipulate, analyze, manage, display and present all types of geographically referenced data, that are data from the real world.

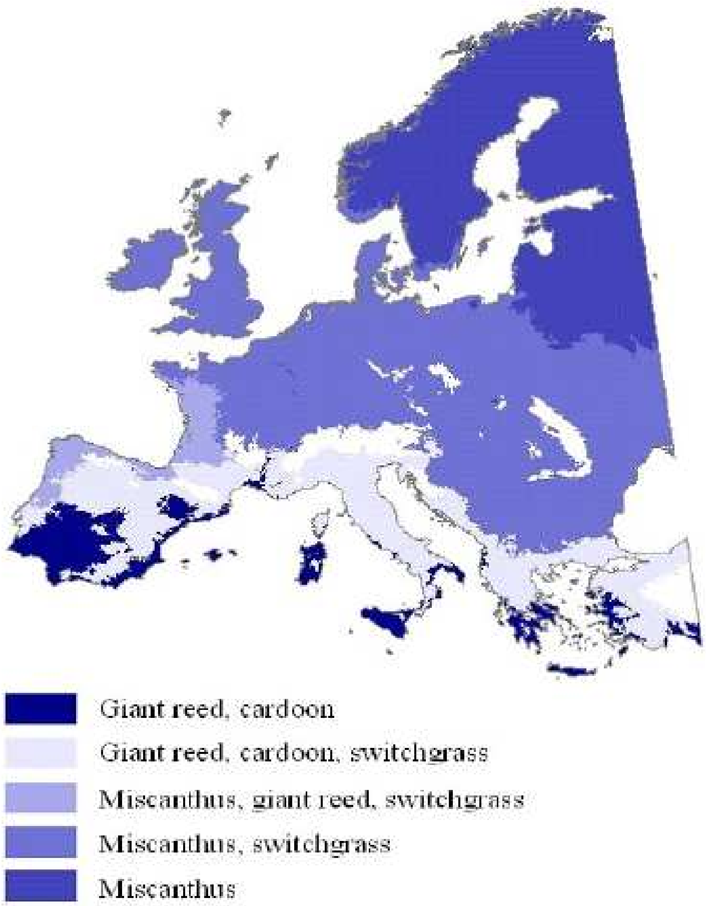


Figure 2.1. Land allocation of perennial energy crops in EU according their climatic requirements from (Zegada-Lizarazu, Elbersen et al. 2010)).

Associated with each geographic feature there is one or more alphanumeric descriptions, organized in table databases. Each row of this table contains the alphanumeric attribute, this last corresponding to the column of the table. With GIS it is possible to manage the characteristics of an area using the computer, then data are in a digital format, allowing to split the environment into several thematic maps, process them and thus to return the responses to specific needs. These tools, consisting of a series of hardware and software (software for spatial data management and analysis, visualization, database management system, descriptive statistics and geostatistics, computer, Global Position System tool, etc.). Further details on GIS can be found in Burrough's book (Heywood, Cornelius et al. 2006), (Burrough and McDonnell 1998), or in the extensive documentation on the web.

The management of all environmental information within a GIS framework allows several advantages in land suitability studies:

- dynamically edit, correct, update and implement all the features of a territory;
- information can be managed and adapted to the needs. (For example, the conditions set for the definition of suitable areas can be changed, you can add more discriminating factors or being more or less rigid in the definition of the optimal range for crops or modifying the accuracy of the suitability map);
- Easy integration within GIS of crop’s growing models, with the possibility to estimate crop phenology and yields based on site-specific growing conditions and then to identify land portions with maximum potential crop yields and quality (Dalla Marta, Mancini et al. 2010).
- allows to change map scale and provide suitability based on the needs of the end user;
- offers the opportunity to focus on a smaller area, such as a Municipality, allowing more detailed analysis, increasing the definition of suitable areas and extracting specific information from the database.
- can be a starting point to increase the dissemination and use of the suitability map as a tool to support decision for farmers and public

institutions operating in the territory, for example with the use of interactive Web GIS packages queried directly from the end user.

It is worth spending a few words about the data that are used in GIS. Data must represent the real word and must be in a digital format. They can be generally acquired by the computer in a vector or raster date model. A vector spatial data model uses two-dimensional Cartesian (*x, y*) co-ordinates to store the shape of a spatial entity. In the vector world the point is the basic building from which all spatial entities are constructed. The simplest spatial entity, the point, is represented by a single (*x, y*) co-ordinate pair. Line and areas entities are constructed by connecting a series of points into chains (lines) and polygons. The raster spatial data model is one of a family of spatial data models described as mosaics. In the raster world individual cells are used as building blocks for creating images of point, line, area and surface entities. Each entity can contain a value. For example the relief of the area can be modelled by giving every cell in the raster image an altitude value. In raster world the basic block is the individual grid cell, and the shape and character of an entity is creating by grouping of cells (fig. 2.2).

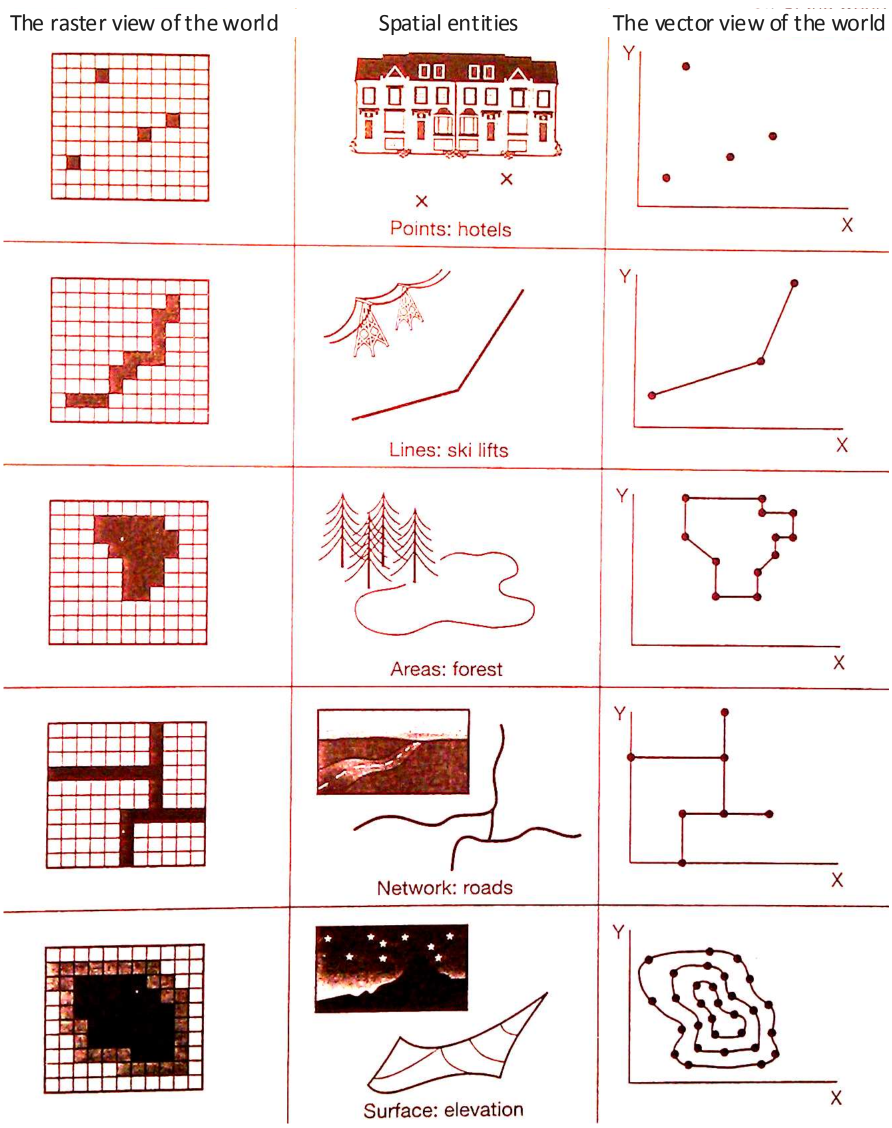


Figure 2.2. Raster and vector representation of the real world (Heywood, Cornelius et al. 2006).

Digital data could also do not be available for a given land portion, or some environmental factors that it are required for the study may be not available. In this case the data acquisition is the most time spending operation: digital map can be produced starting from the traditional cartography or a novel survey must be planned. In general, after more than 30 years of development of GIS, most common data describing the territory, e.g. urbanization, transportation net, hydrology, land morphology, land use, soil maps, climate, etc., are most of the times available, collected by the several private and public institutions that works on the territory for several purposes. Regional information offices, in particular, already own a good part of the spatial data base, with maps already digitized of land use, soil science, geology, soil, hydrology, roads and communication lines, administrative boundaries, contour lines and spot elevations, population, etc. In some cases there are already processed databases to obtain maps like that of the risk from landslides, flooding risk, population's dynamics, etc. As the authors of data are generally different subjects, the homogenization of the data will be needed in order to overlay and correlate them each other.

There is a huge offer of tool and software for the managing of spatial data, both commercially or open-source tools. In the last chapter of this thesis a brief paragraph dedicated to prospects linked with the use of open-sources GIS tools are reported.

The main tool used in this thesis is the commercial software named ArcView3.2. This software is made by the Environmental Systems Research Institute (ESRI) and nowadays is among the most used GIS tool. Actually the system updated to ArcGIS systems, released by ESRI, which structure and approach are different, anyway the previous version ArcView3.2 still is a valuable tool able to carry out several and complicated environmental analysis.

Among the most common operation, as coordinates transformation, data base editing, map editing, vector-raster transformation, map export, etc., key features used in this thesis mainly deal with the topological overlay to relate maps of several environmental factors, contained in the *GeoProcessing Wizard*.

The union operation combines features of an input theme with the polygons from an overlay theme to produce an output theme that contains the attributes and full extent of both themes. Before applying this tool, maps must be converted in vector format with the appropriate converting tool. This operation will be used for example to understand vulnerable land portions for each municipality of the province of Bologna, overlaying municipal borders map with land vulnerability map.

Another used tool was the dissolve operation, that aggregates features that have the same value for an attribute that the user can specifies. For example it were used to aggregate all polygons with the same vulnerable score, or within a defined range, to one single polygon, in order to simplify the map and speed up calculations.

Another important used tool was the map calculator, working with raster data formats. This tool gives the possibility to define a mathematical calculation when overlaying raster maps, producing a single resulting map which pixels are attributed the result of the defined calculation. This tool has been applied when defining land vulnerability map, for which a sum of all vulnerability scores of each involved environmental factors, was carried out to calculate the total score at each location (map cell, or pixel).

GIS is ultimately a useful tool in identifying suitable areas for cultivation of crops, with the study of all environmental factors that define the suitability for a given crop. Several approaches may be used in land suitability studyes for crops. Basically, differences relate to the different weights of importance that are assigned to different environmental factors considered important in influencing the behavior of crops. Another difference is in the statistic methods and multicriteria analysis used to correlate environmental factors each other. In general, after classifying the territory into homogeneous areas according to soil and climatic conditions, a suitability score is attributed as the result of the product among the suitability scores of the various factors for a species. As already mentioned, several factors can be used and must be defined for each specific case study. In general are environmental and climatic factors (e.g. morphology, altitude, rainfall, temperature, fertility, etc..) and socio-economic conditions (presence of towns, streets, industrial areas, typical production, etc.) ((Kasprzak 1992); (Krupa and Kunikowski 2006)). Many studies report the rainfall of an area, the minimum temperatures, daily growing degrees, evapotranspiration, the type of soil. In general, the more factors are introduced, the more the suitability is reliable, reducing the risk of overestimating the extension of suitable areas ((Caldiz, Gaspari et al. 2001); (COTIR-ARSSA 2008)).

Another scheme for land suitability can be learn from distribution of wild plants studies, where what is called ecological profile of a species is generally defined (Carpenter, Gillison et al. 1993). It is ultimately the territorial rules that explain the presence or absence of a species, as resulting from the statistical analysis of characteristics of the stations where the species are naturally present. In the case of cultivated crops, they are the soil and climate characteristics of the places where the species is cultivated in an environmentally and economically sustainability. The definition of local variables determine the niche of the crop and the statistic analysys of those varaibles gives the possibility to find the range of variable linked to the presence of the crop. After this step, potential areas for growing the crop are the ones where the same ranges of environemental variables are found (Carpenter, Gillison et al. 1993).

Focusing on energy crops, a considerable number of studies, at different scale levels, addressed land allocation issues of under current or future climate conditions (Tuck, Glendining et al. 2006). These studies, although approaching with a multivariate procedure, have been generally based on only crop requirements and environmental aptitude to fit these needs (environment-to-crop oriented unidirectional approach). Integrated models also were developed considering several socio-political constraints, which with the help of GIS serving as spatial decision support system ((Rozakis, Casalegno et al. 2001), (Sàez, Varela et al. 2000)).

Anyway GIS have been mainly used to characterize the environment in term of climate, soil and terrain features and then spread crops basing on this characterization, read it as “the best land for a given crop” ((Fiorese and Guariso 2010), (Rozakis, Casalegno et al. 2001); (Krupa and Kunikowsky 2006); (Sàez, Varela et al. 2000)). Briefly, aggregating information coming from different data sets as digitized cartography generally referring to morphology (slope, altitude), soil features (texture and depth, stability, drainage, pH, limestone, organic carbon, nitrogen, carbon to nitrogen ratio, phosphorous and calcium), climate (temperatures and precipitation regimes, accumulation of growing degree days), with description of cultivar agronomic needs from an energy crop catalogue. An example of an Energy Crops Characteristics Catalogue (ECCC) is reported in fig. 2.3.

Sorghum bicolor – *SWEET SORGHUM*

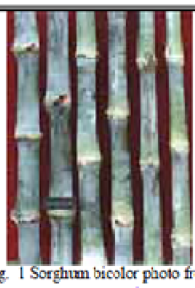


Fig. 1 Sorghum bicolor photo from www.ca.ecoport.org

FAMILY			
LIFE FORM	Grass		
COMMON NAMES			
STRUCTURE	HABIT	PHYSIOLOGY	LIFE SPAN
	erect	single stem	annual
YIELDS	Min.	Max.	
PLANT ATTRIBUTES	grown on large scale, grown on small scale		
CATEGORY	cereals & pseudocereals, forage/pasture, medicinals & aromatic		
FUEL CHARACTERISTICS			

HABITAT		Sweet sorghum has a wide adaptability range. It is drought resistance, waterlogging tolerance, and saline-alkali resistance.
MORPHOLOGY	Roots	It has fibrous, spreading roots. Prop roots may grow from culm nodes.
	Stems	It has an solid, erect, nodose culm or sometimes with spaces in pith, 0.6–5 m tall, depending on variety and growing conditions, 5 to over 30 mm in diameter.
	Leaves	The leaves are broad, dentate, rough-textured, ligulate and ribbed. Similar in shape to those of corn but shorter and wider. Blades glabrous and waxy; sheaths encircle culm and have overlapping margins.
	Flowers	The flowers are grouped in an apical panicle formed by up to 6,000 reddish spikelets. The panicles are erect, sometimes recurved, usually compact in most grain sorghums and more open in forage types.
	Fruits	The fruit consists of an oblong caryopsis. Seeds are white, yellow, red, or brown and covered by glumes that may or may not be removed by threshing. 25,000 to 61,740/kg for grain sorghum; 120,000 to 159,000/kg for grass sorghum.

ENVIRONMENT	OPTIMAL		ABSOLUTE	
	Min	*Max*	*Min*	*max*
Temp. requirement	22	35	8	40
Annual rainfall	400	600	300	700
Latitude	10	30	0	45
Altitude			0	2500
Killing temperature	*during rest: 0*		*early growth: 0*	
Light intensity	*very bright*	*very bright*	*clear skies*	*very bright*

SOIL	pH	depth-m	Texture	Fertility	salinity-dS/m	drainage
OPTIMAL	5,5 – 7,5	medium 0,5 – 1,5	medium, light	moderate	low <4	well (dry spells)
ABSOLUTE	5 – 8	medium 0,5 – 1,5	wide	low	medium 4-10	well (dry spells), excessive (dry/moderate dry)

CLIMAT ZONE	tropical wet & dry (Aw), steppe or semiarid (Bs), subtropical dry summer (Cs)		
Photoperiod	short day (<12 hours)		
Abiotic toler.			
Introduction risk			
USES	Food and beverage (starch, seeds), fodder (stems and leaves), medicinal (flowers), fuels (stems)		
PRODUCTION SYS.	Cropping system: permanent rainfed, sub-system: mono - cropping		
CROP CYCLE	Min. 90, max. 300		

Figure 2.3. The main parameters describing an energy crop based on FAO Databases (ECOCROP2004 2005), (FAO).

The catalogue includes description of each species, of at least of the most common, for quantitative agro-climate conditions evaluation. Attention is on the evaluation of environmental requirements for each species. Those parameters are corresponding with the spatial databases. The additional information such as general description, morphology, distribution or common names are of additional value (Krupa and Kunikowsky 2006). In the Krupa's article, the energy crops description is based on the FAO databases ECOCROP and ECOPORT ((ECOCROP2004 2005); (FAO)).

Through a digital map overlay procedures, the site and the extension of land to be dedicated to a specific energy crop can be defined. Usually, the before mentioned pedo-climatic variables were used as constraints, defining an optimal range able to satisfy agronomic and phytoclimatic characteristics of the crop, out of which land is not suitable.

A novel concept of optimal land allocation: from 'environment-to-crop' toward 'crop-to-environment" approach

As mentioned in the previous paragraph, even if few land suitability studies for energy crops used multivariate procedures and models, even considering socio-economic aspects, basically the approach is anyway environment-to-crop oriented. Growing a crop it also means to use fertilizer, chemicals, fossil fuels, machineries, etc. that also means use of recourses and emissions that bring to an environmental impact. One crop can be more impacting respect to another in relation to the inputs intensification of his production chain. Furthermore, also the same crop may result in a higher or lower impact respect to chosen agronomic technique (zero tillage, low fertilizer input, organic farming, etc.). The environmental effects of crops have been poorly considered or ignored in land suitability studies. As already mentioned when describing LCA for agro-production chain, the link of agriculture with site-specific characteristic of the land where the production chain is located can greatly influence the impact level. In the agricultural sector, the territory, with his variable pedo-climatic conditions, is both a resource and one of the emission target. Moreover, the environment can be more or less sensible to a specific impact, e.g. high sand content soils are more vulnerable to eutrophication respect to a clay soil, because the ability of this last to retain nutrient and then to protect groundwater. The damage of a crop production chain can be different based on the vulnerability level of the location.

The rationale of our approach is therefore to set up a method for crop allocation taking into account the effects of crops to the environment, thus defining a “crop-to-environment” oriented approach. Hence, crops will be selected for a determined environment not only for their productivity but also for their site-specific impacts (bidirectional approach). With the proposed method, the aim is taking into account the mutual crops/environment effect, and it can be seen as a tool to increase the environmental sustainability of land use, following the rule of placing higher impacting crop in lower vulnerable area and the lower ones in the higher vulnerable lands.

Ultimately, this bidirectional approach can be presented as an extension of the land suitability studies, including the environmental impact among the pedo-climatic and socio-economic factors for the definition of the best land portion where to locate crops. Dedicated energy crop production chains will represent instead, as it will be outlined in the case study, a possibility in land use to optimize the environmental sustainability.

Site specific impacts and definition of land vulnerability maps

The site-specificity of the crop impacts defined with LCA, in some way can be dealt with the definition of the maps of vulnerability. The LCA methodology applied to agricultural sector allows to obtain several indicators that define the impact of a crop, due to different impact categories (eutrophication, freshwater toxicity, human toxicity, global warming potential, etc.). The levels of impact of these different categories can be differentiated according to the characteristics of the territory. The tool that allows to relate the impact indicators with the territory is the vulnerability map. It defines the sensitivity of different areas of a territory against a specific impact category.

It can be produced through overlaying land variables that define the land vulnerability to a specific crop impact as calculated by LCA. For each impact it is possible to produce a corresponding land vulnerability map; thereafter, crops may be allocated basing on forward and backward relationships between crop and environment.

GIS is needful to analyze all land factors required to define land vulnerability maps to crop impacts. As for in the environment-to-crop oriented approach, the topological overlay tool is the main operation because it gives the possibility to relate several parameters and to give for each land portion the result of the interaction of all environmental factors that has been considered. Using GIS then it will be possible to identify areas that are sensible for a given impact typology (eutrophication, human toxicity, etc.). Each area may be classified basing on its vulnerable level that may be related to the variability of the factors used to define it.

The vulnerability may be a scalable parameters that can be ranked and also classified. Land portions may be classified for example as low, moderate or highly vulnerable.

For each vulnerable map, the choose of land characteristic to define it, is strictly related with the impact category which the map refers. The lack of literature and the uncertainty in the cause-effect relationship between environmental factors and the vulnerability generates a significant component of randomness in their implementation, providing a quite important component of subjectivity in the method. Based on these premises, ample attention must be toward transparency of recruitment and motivations to justify choices.

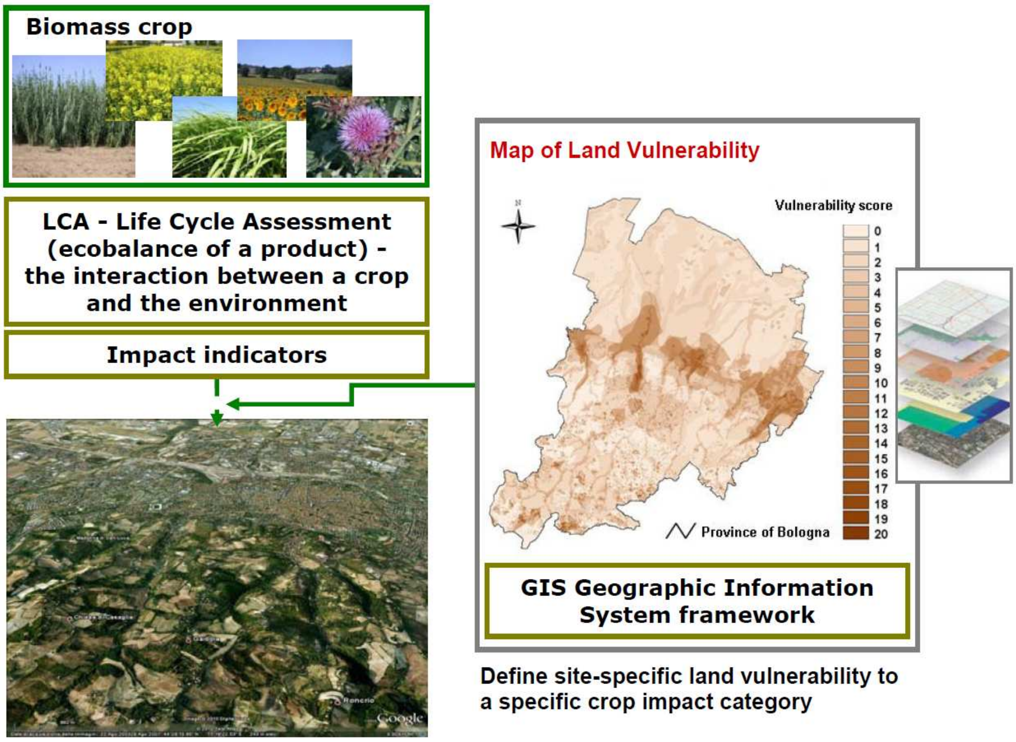


Figure 2.4. Schematic representation of the integration between LCA and land vulnerability.

Integration between LCA and land vulnerability

Once the land vulnerability is understood and the different crops characterized in term of their impacts (e.g. eutrophication), one can allocate the more impacting crops in the less vulnerable areas and *vice versa*. Distribution may occur calculating an “allocation risk value” each allocation scenario. The allocation scenario is defined by a given crop when located in a given vulnerable land. The same crop, when located in a land with low level of vulnerability, to this combination will be attributed a lower allocation risk respect to the same crop located in land classified with a higher vulnerability. At the same time, the comparison is also among different crops. When a location with a given vulnerability level is cultivated with a high impacting crop, the combination will receive a higher allocation risk value respect to when in the same location a lower impacting crop is grown. This allocation risk gives the possibility to compare several crops in several vulnerable lands. This comparison is also given by the definition of the most impacting scenario, i.e. the most impacting crops in the high vulnerable areas. By weighting all scenarios to the most impacting ones gives the possibility to standardize data and them to compare several impacts and several crops.

Fig. 2.5 reports a scheme with a graphical example of the allocation risk calculation in the case of the eutrophication risk. The eutrophication effect of each crop is combined with the land vulnerability and weighted on the worst allocation scenario (maize, the most impacting crop, in the high vulnerable areas). In the territory three classes of vulnerability has been identified (low, moderate and high) (fig. 2.5). For example, in the case of rapeseed when located in the highest vulnerable areas the calculation is as following:

$$82.9 / 100 \times 10 = 8.29$$

where 89.2 % is the eutrophication impact of rapeseed weighted on maize, the most impacting crop. Equally, to calculate the score of rapeseed in the moderate vulnerable areas the formula will be:

$$82.9 / 100 \times 6 = 4.97$$

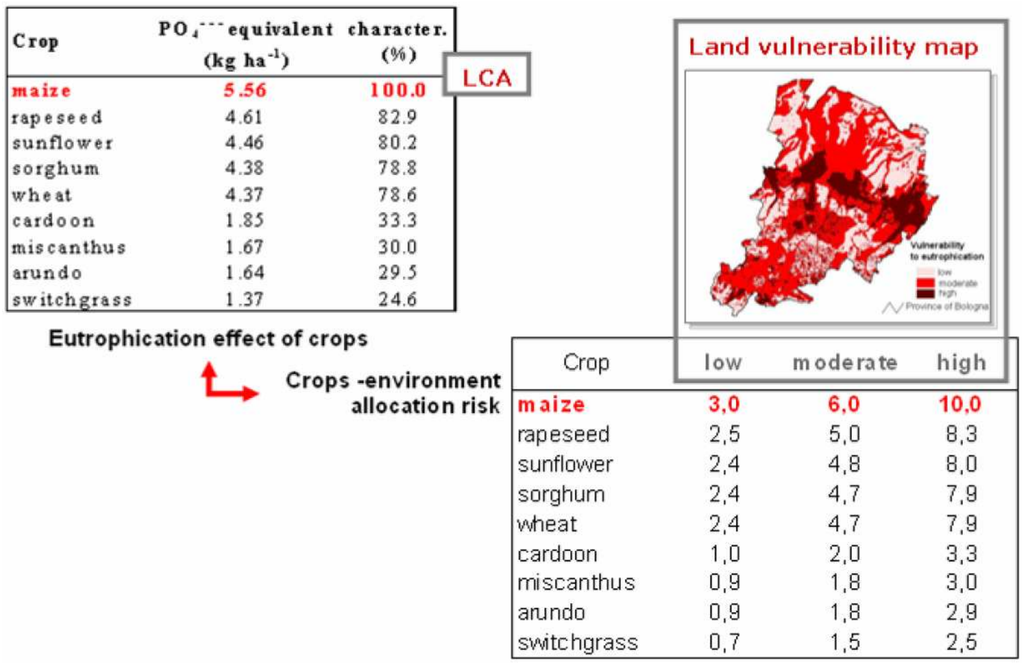


Figure 2.5. Scheme representing the calculation of the crop allocation risk.

The scale can be chosen as from 0 to a maximum of 10. 10 is the value of the worst allocation scenario, 3 and 6 will be the limits for the worst scenario for low and moderate vulnerability lands, respectively. This method is simple and immediate and it is in line with the aim of this study, that is using two well know tool as LCA and GIS to link the impact to site-specific land characteristic. With this approach it is possible to use directly LCA impact results without to go inside their calculation. More refined methods could be developed using models to adjust the value of the impact based on the characteristics of the territory. This requires to know the effect of single emitted substance or used resource on the environment based on the effect of the environment itself on them, that, although desirable, it is still far to be realized unless for specific few of them (e.g. nitrogen losses) (Velthof, Oudendag et al. 2009).

After this calculation, for each vulnerable land portion, the crop with the lowest allocation risk value will ensure the best option from the environmental point of view.

Use of multiple impact indicators to optimize crop allocation

Environmental benefits resulting from combining LCA with the land vulnerability map can be maximized if considering as many as possible impact indicators that can be appraisable with LCA method. The rural area is extremely differentiated, it can include densely populated areas, rivers, farms, hills, etc. It is clear that the effectiveness of the method will be greater the higher the number of impact categories, and in particular impact categories considered relevant to the location.

When working with LCA, there are several methods that can be used to convert input and outputs inventory in an impact for the environment. This phase is the life cycle impact assessment (LCIA), already described in this chapter in the "Life Cycle Assessment for crop production chains" paragraph. The methods available in the literature mainly differs in the characterization factor (CF) and in the number and typology of impact indicators. As already mentioned, the list of impact category indicator values for a production chain under investigation defines its environmental profile. This last, hence, will be different basing on which assessment method is chosen. SETAC-Europe Working Group on LCIA proposed for example the following categories: depletion of abiotic recourses, land use, climate change (global warming), stratospheric ozone depletion, human toxicity, ecotoxicity, photo-oxidant formation (summer smog), acidification, nutrification (eutrophication) ((Udo De Haes, Jolliet et al. 1999a); (Udo De Haes, Jolliet et al. 1999b)). Another assessment method is the CML2 baseline 2000 (Institute of Environmental sciences, Leiden University, NL), this one also selected in this study as referring to the LCA on energy crops carried out in (Monti, Fazio et al. 2009). Table 2.2 summarizes indicators and units. In general these indicators reports impact referring to the main environmental compartments, as water, soil, atmosphere and living organism.

Table 2.2. Impact assessment methods, indicators and units (CML2 baseline 2000 - Institute of Environmental sciences, Leiden University, NL).

Impact category	Units (kg equivalent)
Abiotic depletion	Antimony (Sb)
Global warming power	CO_2
Ozone layer depletion	Chloro-fluoro-carbons 11(ClFCs)
Human toxicity	1,4 dichlorobenzene
Freshwater toxicity	1,4 dichlorobenzene
Marine water toxicity	1,4 dichlorobenzene
Terrestrial toxicity	1,4 dichlorobenzene
Acidification of rainfalls	SO_2
Eutrophication	PO_4^{3-}

These impacts can be, for definition, with global or local effects. For example the target of the global warming potential is the atmosphere at global level. Its effect on the environment is hardly circumscribed. In other words, site-specific conditions able to influence the damage can not be identified. In the LCA-GIS integration, is the impact relation, in terms of potential damage, with site-specific environmental resilience the key aspect and this is calculated through the vulnerability maps. For this reason, only impact indicators with a local effect can be used in the LCA-GIS approach. With local effect we can imagine that a given impact category brings to a damage to the surrounding environmental compartments, i.e. soil, living organisms or water. For example the eutrophication impact of a production chain can affects water and soil where the production chain is located and the vulnerability to eutrophication will depends on the ability of that location to contrast or facilitate damage. In other cases, the vulnerability can also be defined by the distance to a target, e.g. in the case of human toxicity, for which urban areas can be assumed as a target. The distance-to-target approach is a common used principle in the LCA, in particular when dealing with the normalization and evaluation step. Usually refers to a reference value for a given impact indicator decided for example by directives. For example in study of (Brentrup, Kusters et al. 2004), this concept is proposed for the evaluation step in calculating weighting factors. These were derived by using authorized environmental goals like the Kyoto protocol for climate change (Lindeijer 1996). 'Distance-to-target' means a comparison of the current level of an environmental effect in a certain region and time to a target level of the same effect. This concept can be also applied to the local effect concept of impact indicators, where the distance to target can be assumed as an entity geographically placeable, the more the distance of the production chain position, the lower the vulnerability.

Basing on the transparency level of the selected assessment method, local or global effect of indicators, and also of all input and emission involved, is specified within the method details.

Ones defined all impact indicators with local effect of the chosen assessment method, the use of multiple impacts in the LCA-GIS approach will improve at the end the suitability of crop allocation: the vulnerability level of a given land will be calculated basing on more than one impact thus considering several environmental risks, hence increasing the protection level for the environment. The higher the number of impact indicators, the higher the sustainability level.

When working with multiple impacts, few questions may arises: how to combine more than one impact category calculated with LCA? Is an impact more important than another? How to produce a land vulnerability map that considers all involved impact indicators? Looking at the table 2.2, it is possible to see that indicators are quite heterogeneous, they have different units and can not be compared without a sort of standardization. Something that can be compared with the need to define a single indicator that summarize several impacts is what is carried out in the evaluation step of the LCA standard procedure. Normalized values are grouped and weighted to contribute to harm e.g. the natural ecosystems, human health or resources. Results depend on the selected assessment method. Using this concept, it could be defined a unique indicator that groups together all indicators with local effect, namely for example as "local impacts (LI)". This, although advisable, is difficult to obtain because it requires a depth study on relative impacts effects, the choose of weights, a deep knowledge of used assessment methods, databases and LCA software. Of course this aspect could be the object of a dedicated research study.

A simple and fast way to let comparing different impact indicator with local effect it could be to relate impacy of each crop to the worst scenario (a sort of reference situation). Comparing crops, they can be referred to the most impacting crops (e.g. as percentage). This impact portion of an impacting crop is without unit (being a percentage on the most impacting crop), and can be used to calculate a total impact index by making an average of all impacts' % respect to the most impacting crop. Making average brings to a loss of information. An alternative method, or one in which the calculation of a total impact index is not necessary, it would be preferable. The composed multiplicative method (CMM), defined when applying the integration of multiple impact indicators to the case study area (chapter 4), it could be an answer because it does not require the calculation of a total impact index.

Problems in synthesizing impact indicators are the same when dealing with the need to define a comprehensive vulnerability map to relate with a total impact indicator. Again in chapter 4, three alternative methods are defined and tested: simple additive method (SAM); additive method of classified maps (AMCM); composed multiplicative method (CMM). Basically these methods can be grouped in two categories, i.e. with (SAM and AMCM) or without (CMM) an additional operation of synthesis. This operation refers to the calculation of the total impact indicator and the comprehensive vulnerability map.

3. LCA-GIS model design

Case study area description

LCA assessment of selected energy and food crops

Setting up land vulnerability map to fresh water toxicity

Crop allocation for minimizing fresh water toxicity risks

Setting up land vulnerability map to eutrophication

Crop allocation for minimizing eutrophication risks

Setting up land vulnerability map to human toxicity

Crop allocation for minimizing human toxicity risks

Highlights

Case study was composed by 3 impact indicators (freshwater toxicity, eutrophication and human toxicity), 3 annual and 4 perennials herbaceous energy crops, 2 food crops and the province of Bologna. Case study area was characterized by an intensive agriculture in fertile lands, by a small portion of area with underdeveloped agriculture and by a portion of abandoned agricultural lands, where planning strategies and alternative land uses may help to increase rural economy. LCA showed that conventional crops, as maize, resulted in clearly higher impacts than energy crops on all categories. Vulnerability of the province was variable for all impacts. The allocation risk calculation for each crop-vulnerable land combination respect to maize showed that optimal crop allocation to minimize the impact was different on the base of the selected impact indicator. GIS gives the possibility to define vulnerable land portions for each municipality and thus to act for increasing sustainability of land use.

Case study area description

Baseline principles of the proposed method, illustrated in the previous chapter, were applied to a case study are in order to practically define its applicability, to raise criticisms and possible applications of the LCA-GIS integrated tools. The case-study has been limited to a small area (370.000 ha), the Province of Bologna (North Italy, Po Valley). The area was chosen for the availability of digital data readily usable in a GIS format. For this area a considerable number of digital geographic information and metadata are freely available from the digital office that manage the "Geographical Data Catalogue of the Province of Bologna", downloadable at the website http://cst.provincia.bologna.it:81/catalogo/. The catalogue is organized in a web-gis format, where data may be displayed, zoomed and be downloaded in several file formats and geographic reference systems. Also available data for base cartography, as municipal and province borders, urban centres, roads, railways, rivers and lakes, toponymy, etc., which several of them used to facilitate the readability of produced suitability maps.

For the case study area it is also available the "Plan of protection of waters" (ERMESAmbiente 2005) (Piano di Tutela delle Acque - Del. Assemblea Legislativa n. 40/2005 (http://serviziambiente.regione.emilia-romagna.it/PTA/servlet/AdapterHTTP?ACTION_NAME=SCARICA_CARTOGRAFIA_ACTION), where lands sensible or with high risk for water pollution are identified. Maps of this protection plan will be very useful for the definition of following vulnerability maps.

Another important source of information for the case study area is represented by the Land use map, available for the entire Emilia Romagna regional digital office. Last version is updates at 2008 and it represents an important tool for developing of planning strategies at regional and at more local level. Map legend is structured at 4 levels: the first three levels are the same as defined in the European Corine Land cover directives, the fourth is more specifically related to regional land uses. The legend includes more than 80 land classifications, which the minimum represented area, basing on the chosen scale 1.25 000, is of 1.5 ha. A photo book is also attached for each land use category.

All geographical data, before to be analysed, were homogenised in term of reference system and resolution, in order to be each other related.

The province of Bologna is one of the 9 provinces of Emilia Romagna region (table 3.1). He is the province with the higher extension, 3702 km^2, with most of agricultural land classified as intermediate rural area, as defined by the CAP 2007-2013. Small portion of the province is classified as rural area with problems, mainly referring to mountainous part of the province, with a small population density (only 1.3 % of the total residents in the province) and with several infrastructural problem as missing of viability or sleepy lands that make difficult to develop an intensive agriculture (table 3.1). Bologna’s province also contain one of the three urban districts of the whole region corresponding to the Bologna urban area. In general, as also indicated by the rural land classification, Bologna’s province can be characterized by a modern agriculture with intensive crop cultivation in fertile lands, and by a small portion of area with underdeveloped agriculture, where planning strategies and alternative land uses may help to increase rural economy. Also, Bologna's province hosts the higher percentage of population (table 3.1).

Table 3.1. Extension (km^2) and resident population (% respect to the total population of the Emilia Romagna region) of provinces and of rural areas as defined by the CAP 2007-2013.

Extension (Km²)										
Rural area	**Bologna**	**Ferrara**	**Forli - Cesena**	**Modena**	**Piacenza**	**Parma**	**Ravenna**	**Reggio Emilia**	**Rimini**	**TOT**
1-With development problems	790	-	659	947	931	1499	-	731	-	**5558**
2-Intermediate Rural	2772	2633	1029	463	1538	1085	323	543	269	**10655**
3-With specialized agriculture	-	-	691	1095	-	863	1536	1016	266	**5466**
4-Urban area	141	-	-	183	118	-	-	-	-	**443**
Total	**3702**	**2633**	**2379**	**2689**	**2588**	**3447**	**1860**	**2290**	**535**	**22122**
Resident population (%)										
1-With development problems	1.3	-	0.3	1.1	0.4	0.7	-	0.7	-	4.5
2-Intermediate Rural	12.5	8.4	1.4	3.2	3.9	3.1	0.4	2.4	1.1	36.4
3-With specialized agriculture	-	-	7.2	7.2	-	6.1	8.5	8.8	5.8	43.7
4-Urban area	8.8	-	-	4.3	2.4	-	-	-	-	15.5
Total	**22.6**	**8.4**	**9.0**	**15.9**	**6.6**	**9.9**	**8.8**	**11.9**	**7.0**	**100**

Of course, an important amount of population is located in the urban area (8.8 %), but still 12.5 % is located in the rural lands (table 3.1). The anthropic pression in this area is quite important, thus the role of agricultural lands are still more important in answering to territory needs.

Prevalent morphology of the province is flat (1582.67 ha, table 3.2), mainly formed by alluvial soils of the fertile Po river valley. The hilly area is found in 1330 ha, while inland mountainous area are 790 ha (table 3.2).

Table 3.2. Prevalent morphology (ha) of provinces of the Emilia Romagna region.

Province	inland mountain (ha)	inland hill (ha)	coastal hill (ha)	plain (ha)	Tot surface (ha)
Province of Piacenza	932.0	950.3	-	707.2	2589.5
Province of Parma	1499.8	1086	-	863.5	3449.3
Province of Reggio Emilia	731.8	543	-	1018.1	2292.9
Province of Modena	947.3	462.8	-	1272.9	2682.9
Province of Bologna	790.1	1330	-	1582.7	3702.4
Province of Ferrara	-	-	-	2631.8	2631.8
Province of Ravenna	-	323.3	-	1535.2	1858.5
Province of Forli-Cesena	659.0	1028	-	690.0	2376.8
Province of Rimini	-	61.91	206.8	264.6	533.3
Total	**5560.0**	**5785**	**206.8**	**10565.8**	**22117.3**

Table 3.3. Land uses (ha) in the provinces of the Emilia Romagna region based on statistical data referring to the 5[Th] National Census on Agriculture, carried out in 2005 by the Italian National Office of Statistic (ISTAT).

Area	Total Agricultural Area (TAA)	Utilized Agricultural Area (UAA)	% on UAA of arable lands	% on UAA of pastures	% of forests
Province of Piacenza	165 945	125 589	80.56	10.00	20.90
Province of Parma	194 470	134 125	61.39	15.30	36.85
Province of Reggio Emilia	136 180	107 429	88.56	0.35	1.12
Province of Modena	179 479	137 047	70.91	14.53	17.89
Province of Bologna	256 702	187 057	79.79	10.58	21.19
Province of Ferrara	201 148	179 173	81.80	17.06	34.49
Province of Ravenna	142 913	117 246	61.47	2.07	8.95
Province of Forli-Cesena	155 968	98 462	72.87	17.69	14.39
Province of Rimini	34 434	29 252	78.53	2.55	5.47
Total	**1467239**	**1115380**	**76.23**	**10.10**	**18.14**

Among the provinces, Bologna also has the highest amount of agricultural lands (256702 ha), which 187057 ha are cultivated (table 3.3). Almost 80 % are arable lands, where herbaceous energy crops taken into account in this study may readily and easily being grown.

Table 3.4. Number of farms and their total and used agricultural lands each province of the Emilia Romagna region based on statistical data referring to the 5Th National Census on Agriculture, carried out in 2005 by the Italian National Office of Statistic (ISTAT).

Province	Farms (N°)	Total Agricultural Surface of farms (ha farm-1)	Used Agricultural Surface of farms (ha farm-1)
Bologna	17496	14,67	10,69
Forli-Cesena	14968	10,42	6,58
Ferrara	10935	18,39	16,39
Modena	14711	12,20	9,32
Piacenza	9038	18,36	13,90
Parma	11009	17,66	12,18
Ravenna	11876	12,03	9,87
Reggio Emilia	11357	11,99	9,46
Rimini	6498	5,30	4,50
Total	**107888**	**13,60**	**10,34**

Number of registered farms in the province are 17496 (table 3.4), the higher in the whole region, which extensions are 14.67 ha per farm and 10.69 ha of used agricultural lands. Farms are on averaged larger in the province of Ferrara (18.39 ha) and Piacenza (18.36 ha). Number of farms deceased of 35.38 % (table 3.5) in 10 years (from 2000 to 2010). 57.95 % of farms decreased in the mountain area, against 27 % in the flat area and 36.14 % in hilly area. Used agricultural lands decreased of 7.18 % in the whole province, meaning that most of closed farm were incorporated by others, anyway in the mountain area used agricultural lands decreased of 31.03 % and in the hilly area of 19.58 %. Apart of reasons that brought land abandonment, not among the aims of this study, those land portions could be part of a planning strategy to increase the rural income.

Table 3.5. Evolution of number of farms in the province of Bologna and per altitude class (RER 2011). Used agricultural land (UAL), total agricultural lands (TAL).

http://www.regione.emilia-romagna.it/wcm/statistica/censimenti/censimenti/censagri_2010.htm

Altitude class	Farms (N) 2010	Farms (N) 2000	Variaz. %	UAL 2010	UAL 2000	Variaz. %	TAL 2010	TAL 2000	Variaz. %
Mountain	1 287	3 061	**-57.95**	12 131.46	17 589.41	**-31.03**	23 256.29	34 648.49	**-32.88**
Hill	3 145	4 925	**-36.14**	45 163.25	56 161.15	**-19.58**	72 151.53	84 079.42	**-14.19**
Plain	6 353	8 703	**-27.00**	116 299.28	113 280.82	**2.66**	133 250.84	130 201.32	**2.34**
Total	**10 785**	**16 689**	**-35.38**	**173 593.99**	**187 031.38**	**-7.18**	**228 658.66**	**248 929.23**	**-8.14**

Table 3.6. Agriculture main land uses in the province of Bologna and for altitude class (RER 2011).

http://www.regione.emilia-romagna.it/wcm/statistica/censimenti/censimenti/censagri_2010.htm

Morphology	sowable (ha) 2010	sowable (ha) 2000	tree crops (ha) 2010	tree crops (ha) 2000	grass and pastures (ha) 2010	grass and pastures (ha) 2000
mountain	6 394,00	9 092,98	463,56	874,56	5 248,45	7 594,75
hill	32 039,11	38 551,07	6 084,59	7 594,01	6 913,59	9 944,50
plain	103 180,74	98 506,69	10 930,97	14 112,41	2 051,64	580,37
Total	**141 613,85**	**146 150,74**	**17 479,12**	**22 580,98**	**14 213,68**	**18 119,62**

The picture, updated to provisional data released by the last ISTAT Census on Agriculture (2010), reports 6394 ha of sowable lands in the mountain, 32039 ha in the hilly area, and 103180 ha in the flat area (table 3.6). Also a good amount of grasses and pasture, that may be considered for alternative land uses with herbaceous energy crops, are present in the hilly area and mountainous. Hilly fields are maybe the one that can be more easily converted with biomass crops.

In fig. 3.1 main geographic and topological characteristics of the province of Bologna are represented.

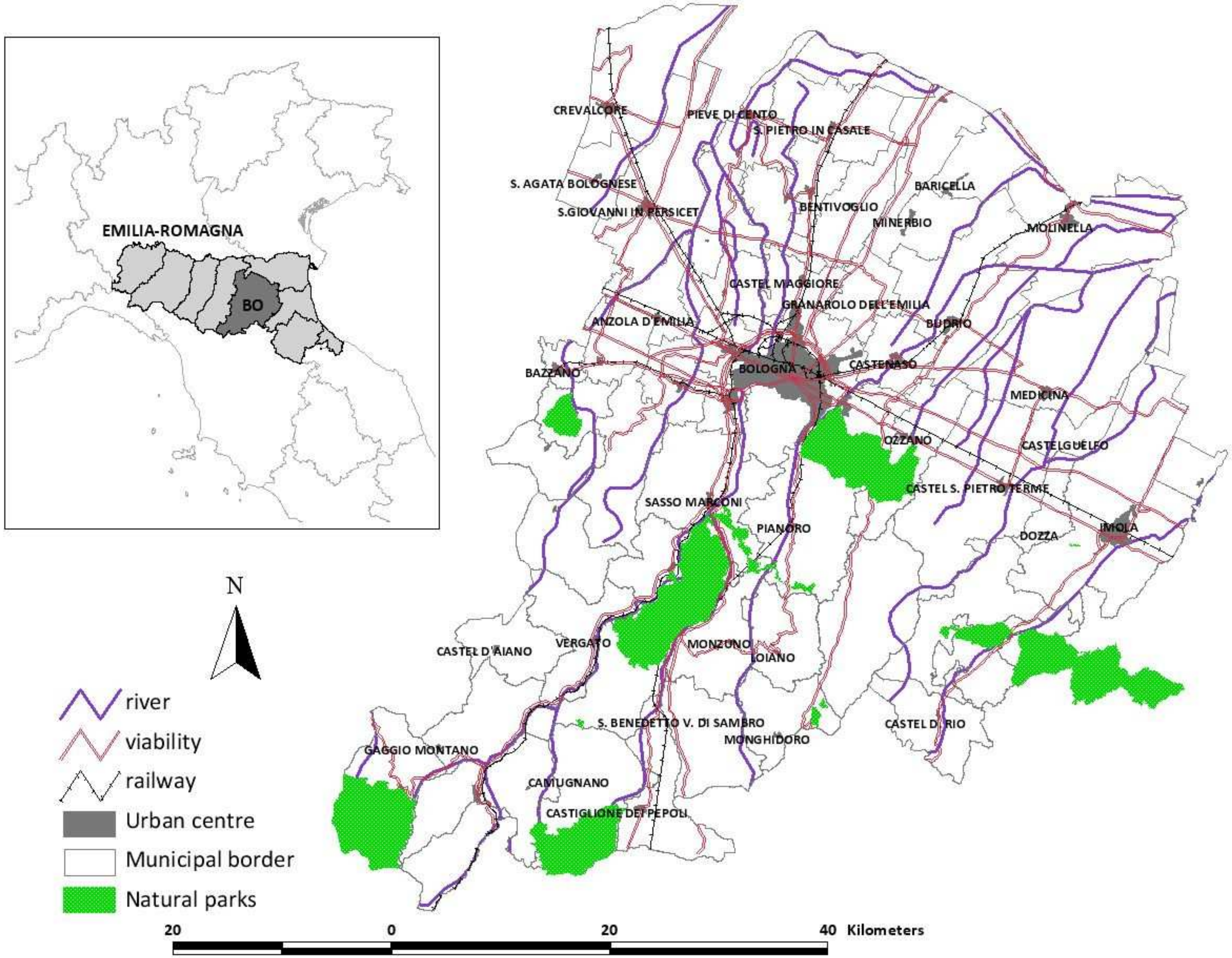


Figure 3.1. Province of Bologna (case study area).

LCA assessment of selected energy and food crops

In order to test the principles of the proposed LCA-GIS integration approach, some herbaceous annual and perennials, among the most promising, energy crops were chosen. At the same time, also some LCA impact indicators, among the one with a local effect appraisable with LCA (LCA, ISO 14040-43), were used to estimate 3 impact indicators. These where at the end used as samples to define the method for land allocation taking into account both one impact indicator or integrating more than one environmental impact. Chosen impacts were eutrophication (EU), human toxicity (HUMT) and freshwater toxicity (FWT) charges, following the cultivation of rapeseed (*Brassica napus* L.), sunflower (*Helianthus annuus* L.), fibre sorghum (*Sorghum bicolor* L.), giant reed (*Arundo donax* L.), cynara (*Cynara cardunculus* L.), miscanthus (*Miscanthus x giganteus* greef & Deuter) and switchgrass (*Panicum virgatum* L.) compared to wheat (*Triticum* spp. L.) – maize (*Zea mais* L.) rotation. The rotation wheat-maize (50/50) was assumed as reference scenario of conventional cropping systems. Cradle-to-farm gate impacts of each crop were compared on land (hectare) basis, that allows to compare products with different purposes (e.g. food crops and energy crops). According with the standard procedures ISO 14040-43, the analysis was divided into four steps: (i) goal and scope definition where system under study is defined; (ii) inventory (LCI), input and output data of the crop production chains are collected and analysed; (iii) impact assessment (LCIA), the emissions in air, soil and water, as well as raw materials and energy consumptions, are standardized and translated into environmental effects. CML2 baseline 2000 (Institute of Environmental Sciences, Leiden University, NL) was chosen as impact assessment method; (iv) interpretation, which aimed at identifying weak points and possible improvements of the processes. Details on LCA metadata and inventory of all crop production chains are described in (Monti, Fazio et al. 2009). LCA results were directly taken by that study, showing how this methodology could use LCA results from the bibliography, without to accomplish further particular work in adaptation, at least if the standard procedure is followed during LCA. Crops and LCA carried out in mentioned study (Monti, Fazio et al. 2009), referred anyway to data inventory and measures directly carried out in, and of tipical agronomic practices of, the territory chosen as case study area.

SimaPro 7.0 (PRé Consultants, Amersfoort, NL) was adopted to model and analyse the different scenarios. Eutrophication, for example, was calculated as following:

$$EPi = (Vi/Mi) \bullet (Mref/Vref)$$

where Vi and Vref (dimensionless) are the potential contribute to eutrophication of a generic compound (*i*) and the reference (expressed as kg ha^{-1} equivalent phosphate ions), respectively; Mi and Mref are the weights of *i* and reference, respectively. More in general, the impact indicator (ICi) were calculated as following:

$$ICi = \sum_j E_j \cdot CF_{i,j}$$

Ej is the emission release or the consumption of the generic resource j, and CFi,j is the characterization factor of j substance that contributes the i-category. The characterization factor is the relative contribution of a compound to the impact category. Details on LCA calculation results are reported in (Monti, Fazio et al. 2009).

Inventory data were extracted by the widespread dataset Ecoinvent 1.1 (Swiss Centre for Life Cycle Inventory, Zurich), that in some case was found too generic for some agronomic practices, therefore Ecoinvent 1.1 integrated with other data collected by crop handbooks, interviews and direct measurements in the experimental of the University of Bologna, located in Cadriano (Monti, Fazio et al. 2009). Generally, the most conventional conventional agronomic practices were assumed for each crop.

In table 3.7 are reported the impacts results for the case study of all food and no-food production chains used for the definition of the LCA-GIS approach and for combining multiple impact indicators.

Conventional crops resulted in clearly higher impacts than energy crops on all impact categories. Maize was in general the crop that showed the higher impact, while switchgrass the lowest, on hectare basis. The relatively good performance of switchgrass (table 3.7 and 3.8) may be principally attributed to two main reasons: the lower incidence of P-fertilization in this crop with respect to the other rhizomatous crops, and the different propagation technique, switchgrass being seedable while giant reed and miscanthus are not. As for switchgrass, also cynara is a seedable crop, however the short lifespan (five years) parallel with a low productivity in the case study area, determined a significant higher incidence of environmental loads in this crop. Again, generally, N-fertilization, crop establishment and harvest were mainly contributed in defining the impact. More details on the relevance of the major agronomic practices on total environmental impact are reported in (Monti, Fazio et al. 2009).

Table 3.7. Eutrophication value (EU, expressed as kg ha^{-1} of equivalent phophate ions (PO4-3 eq.), human toxicity (HUMT) and toxicity to freshwaters (FWT), these two last expressed as kg ha^{-1} of 1,4-diclorobenzene eq. (1,4-DC eq.), and as % respect to the highest impacting crop (maize). The total impact index is calculated as average of the % values of impacts: [EU%) + (HT%) + (FWT%)] / 3.

Crop	**FWT 1,4-DC eq. (kg ha^{-1})**	**%**	**EU PO_4^{3-} eq. (kg ha^{-1})**	**%**	**HUMT 1,4-DC eq. (kg ha^{-1})**	**%**	**Total impact index %**
maize	**199**	**100**	**5.56**	**100**	**1810**	**100**	**100**
f sorghum	128.0	**64.3**	4.38	**78.8**	1360	**75.1**	**72.7**
rapeseed	101.0	**50.8**	4.61	**82.9**	1150	**63.5**	**65.7**
wheat	99.1	**49.8**	4.37	**78.6**	1180	**65.2**	**64.5**
sunflower	90.5	**45.5**	4.46	**80.2**	1150	**63.5**	**63.1**
cynara	74.3	**37.3**	1.85	**33.3**	738	**40.8**	**37.1**
miscanthus	76.9	**38.6**	1.67	**30.0**	709	**39.2**	**36.0**
giant reed	73.9	**37.1**	1.64	**29.5**	661	**36.5**	**34.4**
switchgrass	50.3	**25.3**	1.37	**24.6**	474	**26.2**	**25.4**

FWT, EU and HUMT reached the highest value for maize, meaning that maize can be considered as the most impacting crop. The other crop, therefore, can be compared to maize. The % value give an idea on how other crop are less impacting respect to maize. Looking at FWT, f sorghum is the highest impacting crop after maize (64.3 % of maize impact), followed by rapeseed, wheat, sunflower, where impact are half of maize (table 3.7). The perennial herbaceous crops showed a lower FWT impact. Among these last, higher impacts are for miscanthus. Switchgrass has the lower FWT impact, significantly lower than maize (25.3 % of maize) and in general also respect to the other perennials. EU impact is still the highest in the case of maize, followed by rapeseed, sunflower, sorghum and wheat, all representing between 78.6 % to 82.9 % of maize's impact. Again perennial crops showed a significantly lower EU impact, from 24.6 % to 33.3 % respect to maize (table 3.7). HUMT impact was high for f sorghum, after maize, representing his 72.7 %. Rapeseed, wheat and sunflowers were around 65 % respect to maize, and still perennials showed a low impact respect to maize and other annual biomass and food crops, ranging from 25.4 % to 37.1 % (table 3.7).

Among the LCA-GIS method development aims, one task is also to allocate crop considering at the same time more than one impact indicator. It could be therefore useful to define a total impact index that in a sort of way summarize all impacts with local effect that are used, thus it can be related to a comprehensive vulnerability map. The definition of this total indicator could follow several approaches that wants to compare variables with different units and of different orders. Table 3.7 reports a total impact indicator respect to the highest impacting crop. This total indicator, calculated as a mean between FWT%, EU% and HUMT%, would represent a simple and immediate way to include in one indicator the freshwater toxicity, the eutrophication and the human toxicity impact, standardized respect to the highest impacting crop (maize). Referring to this total impact index, after maize, f sorghum again showed the highest overall impact (72.7 % respect to maize), followed by rapeseed, wheat and sunflower (table 3.7). Poliennal crops resulted in a quite low impact respect to maize and the other annual crops, in particular switchgrass with 25,4 % respect to maize (table 3.7).

In table 3.8 are reported impact values ordered from the highest to the lowest impact respect to each impact indicator and respect to the total impact index. Giant reed and switchgrass were definitely in all cases the lower impacting crops. Cynara was the higher impacting crop among the perennials except for FWT. Perennial crops (cynara, miscanthus, giant reed and switchgrass) are similarly impacting in all cases.

Table 3.8. Crops ordered from the higher to the lower impact value.

FWT 1,4-DC eq. (kg ha^{-1})	EU PO_4^{3-} eq. (kg ha^{-1})	HUMT 1,4-DC eq. (kg ha^{-1})	Total impact index
maize	**maize**	**maize**	**maize**
f sorghum	rapeseed	f sorghum	f sorghum
rapeseed	sunflower	wheat	repeseed
wheat	f sorghum	repeseed	wheat
sunflower	wheat	sunflower	sunflower
miscanthus	cynara	cynara	cynara
cynara	miscanthus	miscanthus	miscanthus
giant reed	giant reed	giant reed	giant reed
switchgrass	switchgrass	switchgrass	switchgrass

Fibre sorghum resulted as the second highest impacting crop (after maize) if considering all impact categories, thanks to the higher value of human and freshwater toxicity. Rapeseed resulted in a high value of eutrophication that led to be in general the third highest impacting crop.

As already described in chapter 2 “Baseline principle”, the attempt to link LCA impacts with site-specific environmental characteristics includes the definition of land vulnerability maps of the study area to chosen impact indicators (FWT, EU and HUMT), described in following pages.

Setting up land vulnerability map to fresh water toxicity

For the definition of the land vulnerability map referring to the freshwater toxicity, several land characteristics are available in a digital format in the “Plan for Protection of Waters“. This plan is produced at regional level by the Emilia Romagna Region and it provides for each province a map with the indication of land portions for the protection of fresh and underground waters (EPS 2009). The aim is to ensure an optimal underground water recharge and the protection of standard quality requirements for drinking water. Thus, defined areas in the included maps are directly or indirectly linked with water and for this reason they could be considered as sensible to substances eventually released by production chains, because of the potential damage to water quality and quantity, and then setting the vulnerability for freshwater. In general, within the hilly part of the province of Bologna, these vulnerable areas are represented by the end of the alluvial fans and foothill aquifers, while in hilly mountainous part of the province, these areas are identified on the basis of the presence of captured water for water grid destination. As regard to surface waters for human consumption, vulnerable areas are in general the ones affecting watersheds drained from drinking water outlets. In the plan for the protection of waters, the protected area delineation has been carried out considering different aspects, such as the analysis of qualitative and quantitative data collected from a groundwater monitoring network. For example, if nitrate fluctuations is fast, it means that there is a direct recharge of the aquifer, whereas if fluctuations are regular and continuous, it means that there is an indirect recharge (see e.g. Type areas B in the following classification). Other used environmental information, among the others, were the available geological mapping and the isotopic geochemistry of groundwater. The details of the entire protection plan implementation are contained in the technical report accompanying the produced maps (Severi and Bonzi 2008).

The plan for the protection of water released by the Emilia Romagna region has been used as starting base for the production of the vulnerability map to freshwater toxicity. Through the study on the reported environment analysis and the integration with several factors in order to better fit the targets of the PhD study, the Province of Bologna has been classified in the following categories:

1. **Groundwater protection areas in foothill and lowland territories**. The protection of these areas has the purpose of protecting and preserving the natural process of aquifer recharge, ensuring the preservation of the ability to rebuild the resource available for various uses, including use for drinking water largely bypassed by groundwater, and also to limit the waterproofing of areas where soils are permeable. These areas are ultimately areas of groundwater recharge, several distinct typology are listed below:

   Type D: represented by the adjacent bands to river streams with side prevailing feeding the under level riverbed; this area can not be used for the new development and then soil sealing, in order to maintain quantitatively the water charging function. The D area border is defined by considering a geometrical method, 250 meters around the main rivers and streams that run through areas of type A and B, below described. Areas with gravel surfacing associated with the aquifer, and the more recent alluvial terraces attributed to the rivers were selected. The presence of a plentiful and of good quality water course is a positive element for the maintenance of groundwater quality. The rivers have in fact a diluting power against pollutants eventually dissolved in the underground water, then the areas where there is the transfer of water from the river to water table should be protected, or, in other words, eventually only cultivated with low impacting crops. For their definition we have used the areas adjacent to streams where they were present outcrops and gravels associated with the aquifer, and the more recent alluvial terraces and attributed to the rivers.

Type A: areas with direct recharge of the aquifer, gravel surfacing and continuous in the subsurface for tens of meters; river terraces connected ideologically, hydrogeologically identifiable by a single-layer system containing an aquifer in continuity with the surface from which it receives waters for infiltration. In these areas the new urbanism is strongly conditioning. The same could be imaged for crops that in these areas must release the least amount of pollutants as the direct connection with fresh water. Type A areas, thus, must be considered with high vulnerability. A greater vulnerability it may be recognized to type D areas, respect to type A, for its further function of water charging and the diluent effect of pollutants.

Type B: areas characterized by indirect recharge of the aquifer, where there is an indirect relationship with the groundwater and with no gravel surfacing presence. The presence of soil makes a filter function that it lowers the vulnerability of this area.

Type C: catchment basins of water supply for recharge areas of type A and B, linked to the fact that the runoff surface waters toward valley are able to recharge downstream areas. The runoff and the distance from the target that are the charging areas of type A and B, allows to assign a lower vulnerability to this category.

All above mentioned land categories, all part of the **groundwater protection areas in foothill and lowland territories**, are considered highly vulnerable to fresh water toxicity. Basing on the set of rules for the protection of fresh waters (ERMESAmbiente 2005), for example, all livestock activities, e.g. spreading of manure, fertilizers, sewage sludge and pesticides, must be regulated. For the production of the vulnerability map to fresh water toxicity, all the above mentioned areas has been organized in a map layer (ESRI shape file format) called "*PTCP_recharge_areas_abcd.shp"*. This layer will be overlaid with other environmental characteristics in order to produce the vulnerability map to freshwater toxicity.

2. **Zones of protection of surface waters**. Consists of areas of protection of water reserves, i.e. basins that feed reserves for drinking water supply wells, and of regional concern. They are basin at the upstream of the intake (10 km^2 above the intake and 5 km river along the riverbed). Regarding more specifically the areas of protection of surface waters, protection of these areas is aimed at maintaining water quality that are invoked by the collection systems, to avoid or mitigate the risk of spills of pollutants that through runoff may reach water bodies, avoiding the consumption of soil and protect the self purification capacity of rivers. Based on these reasons, the vulnerability to toxicity to freshwater is considered quite high for this category. These areas are reported in the ESRI shape file map layer called "*PTCP_zones_derivat_prot.shp*".
3. **Zones of protection of surface and groundwater in foothill and mountain territories**. Includes rocks stock, main exploitable aquifers for drinking water supply (water sources), and fluvial terraces constituting the recharge areas that feed the river in the low flow periods, contributing to its flow. May be ideologically connected to rivers or not. In these areas, the waters runoff on the surface and in the lower river network end at valley and then actually feed the downstream rivers. Moreover, other zones of protection of groundwater are also indentified in the hilly and mountainous areas, such as natural emergence of groundwater (and related water sources phenomena), and the reserve areas

(areas within the areas of groundwater recharge, referring to untapped sources, but with a potential potable use). This category includes the following map:

- *supply_areas.shp*
- *recharge_areas.shp*
- *buffer_weels.shp*
- *reserve_areas.shp*
- *PTCP_fluvial_tut_areas.shp (areas of protection of fluvial terraces)*

Figure 3.2 shows all above mentioned land classification extracted from the Plan for Protection of Waters, and used for the definition of the land vulnerability map to freshwater toxicity. Reserve and recharge areas are mainly located in the mountainous part of the Province. Most vulnerable areas are anyway the ones located in foothill and lowland territories, zones for the protection of groundwater, referring to the central area of the map, corresponding to the end of the hilly morphology and the beginning of the flat area. Overlaying these map layers with urban centre map or other topographic information (not reported in this thesis), it is possible to see how the anthropic pressure on these areas is quite high. Most populated urban areas, and consequently road and transport infrastructure, are in general located in the central part of the province. Still, the agricultural land is quite integrated with the urbanization, thus appropriate land planning of agriculture may help in reducing land vulnerability or decreasing negative effects of human activities on freshwater.

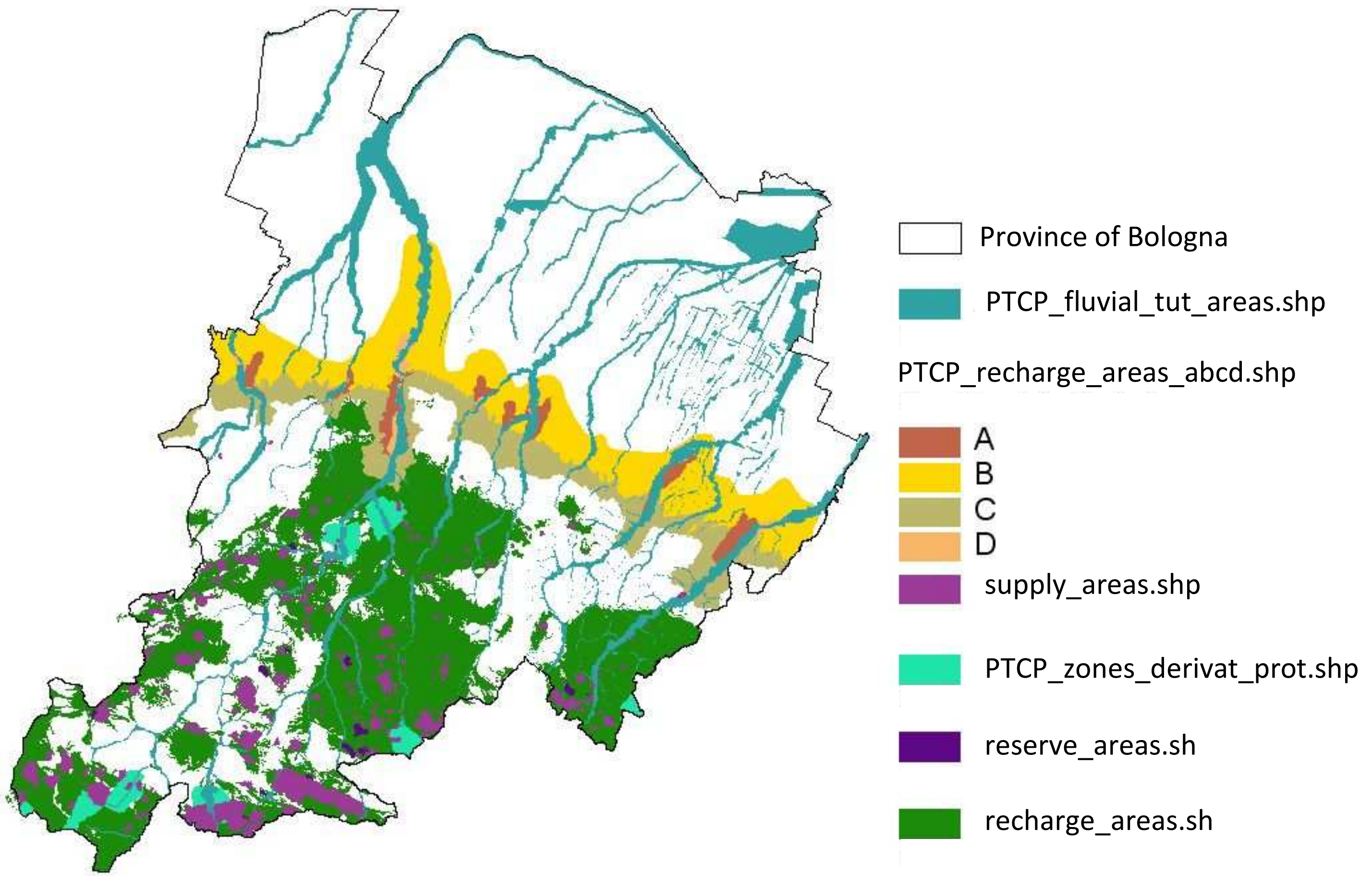


Figure 3.2. Environmental layers used for the production of the vulnerability map to freshwater toxicity. Map layer are extracted from the "Variation to the Provincial Coordination Plan for the implementation of the Plan for the Protection of Waters"(EPS 2009).

As already mentioned, the limitations related to the use of all these areas, basing on the purposes of the plan for protection of fresh waters for human consumption, are in the soil consumption and waterproofing, in order to ensure water and springs charging. Basing on this aspect, areas most directly related to the aquifer and the springs have major limitations. The same concept can be applied against the vulnerability to freshwater toxicity. The areas most directly related to the groundwater, such as river areas, areas with gravel surfacing (type D and A), are also less suitable to host activities that release harmful substances for the aquifer, then receive a high vulnerability score to the toxicity of fresh water. Vice versa, to areas not directly connected with the aquifer, can be recognised a lower vulnerability score. The presence of soils that are different from the surface gravels, which the runoff water and percolation meet before reloading groundwater, may make a filtering mechanism and then decrease the damage to the aquifer, and consequently receive a lower value of vulnerability score (Type C and Type 3).

Among the various constraints applied to identified areas in the Protection Plan, which are primarily related to new town planning in order to limit the waterproofing and contamination of groundwater by urban sewage, it is also required for agronomic practices to avoid the dispersion of nutrients and pesticides to groundwater. Spreading of liquid manure on agricultural land also requires compliance with related regional rules.

Basing on the specific characteristics of classified lands illustrated in the Protection Plan, it is possible to qualitatively rank all land layers against the vulnerability level to freshwater toxicity, on the base of the direct link and the distance from the target (i.e. fresh surface water and groundwater) principle:

Type D **>** Type A and supply_areas.shp **>** PTCP_zones_derivat_prot.shp and PTCP_fluvial_tut_ares.shp **>** Type B **>** Type C, recharge_areas.shp and reserve_areas.shp.

In order to take into consideration the contribution of all the environmental variables, it is possible to assign a score of vulnerability according to a scale by 1 to 5, being 5 the clusters identified on the base of the above qualitative ranking. Assigned vulnerability scores are showed in table 3.9.

Table 3.9. Vulnerability scores assigned to map layers used for the definition of the vulnerability map to fresh water toxicity.

Map layer	Map layer attribute	Vulnerability score
PTCP_recharge_areas_abcd.shp	Type D	5
PTCP_recharge_areas_abcd.shp	Type A	4
supply_areas.shp	Water supply areas	4
PTCP_zones_derivat_prot.shp	Zones for the derivations protection	3
PTCP_fluvial_tut_areas.shp	Zones for the protection of the riverbeds	3
PTCP_recharge_areas_abcd.shp	Type B	2
PTCP_recharge_areas_abcd.shp	Type C	1
recharge_areas.shp	Recharge areas	1
reserve_areas.shp	Reserve areas	1

All layers have been converted to raster map with the same resolution (50 m pixel) and extension (province of Bologna), and then overlaid using the map calculator tool of ArcView3.2 (ESRI).

For each pixel, the map calculator tool summed the vulnerability score. The resulting map is a raster map with the total vulnerability score for each pixel. The vector format (map_calc_vuln_FWT.shp) is showed in fig. 3.3. Vulnerability score ranged from 0 to 11. Where value is zero, no limiting condition, referring to table 3.9, are present. There are no areas where are all limiting factors are present in the same location. Resulting total vulnerability scores were classified in 3 classes (low, moderate and high) of vulnerability in order to simplify the map visualization, following the equal area approach. The vector format of this map is showed in fig. 3.4. Polygon of this map where aggregated based on the vulnerability classification, using the dissolve tool of the GeoProcessing Wizard of ArcView3.2. This operation aggregates features that have the same value for an attribute that user can specifies.

Higher vulnerable area are located in the centre of the province, and they are linked to the riverbed track. Few small area are present in the Apennines (lower part of the map), mainly related to the presence of reserve areas.

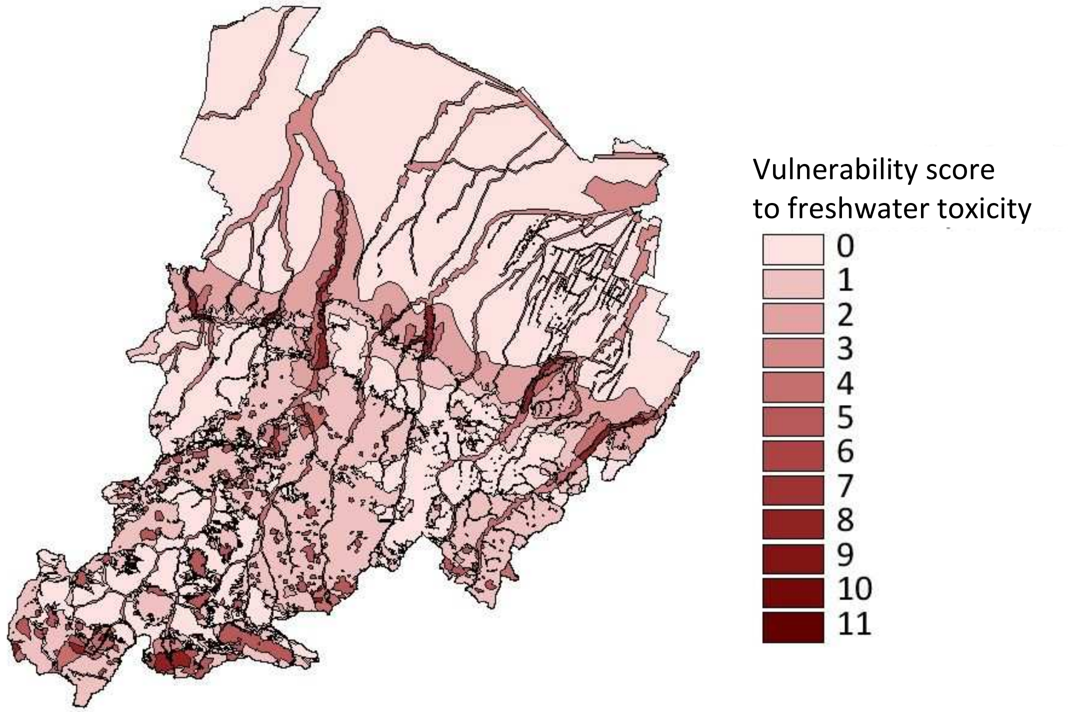


Figure 3.3. Vulnerability map to fresh water toxicity. This map is the result of the topological overlay of land classifications extracted from the Plan of protection of fresh waters.

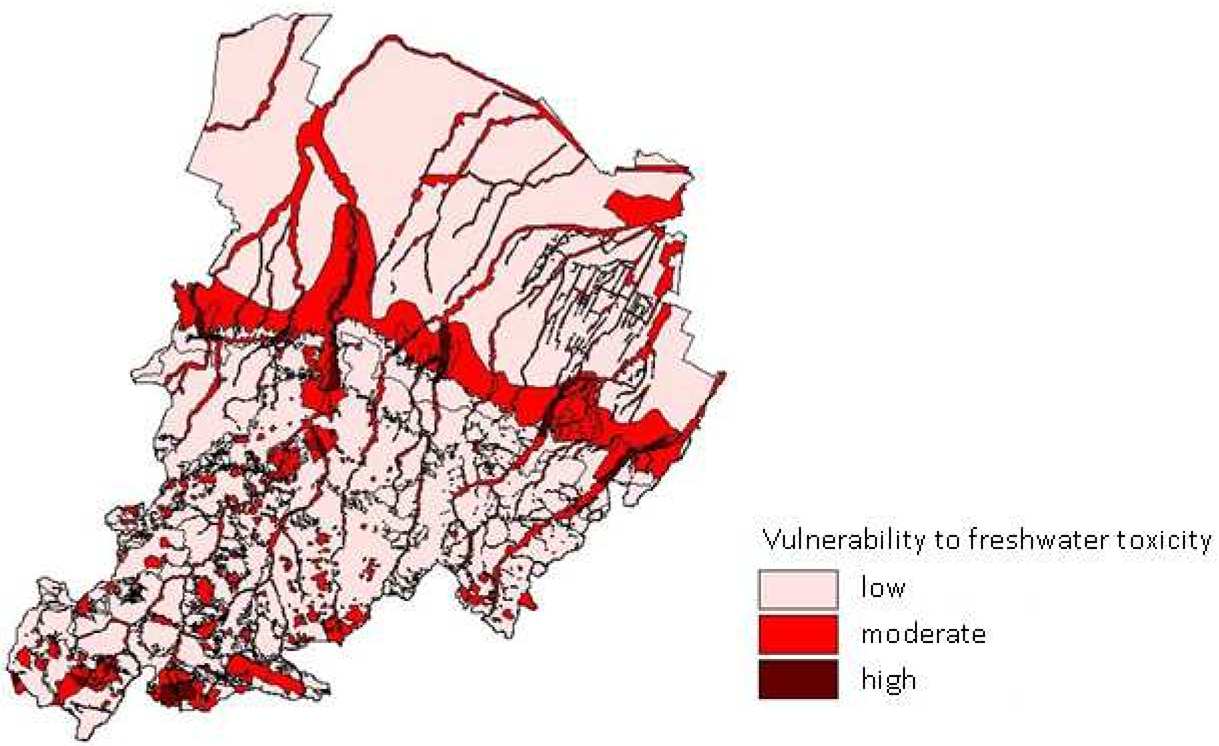


Figure 3.4. Vulnerability map to fresh water toxicity (FWT) with classification of the total vulnerability score in 3 classes of vulnerability: low (0 – 1); moderate (2 – 6), high (7 - 11), based on equal area classification.

Table 3.10. Vulnerability to freshwater toxicity (FWT) of municipalities in the Province of Bologna.

Municipality	low (%)	moderate (%)	high (%)	Total (ha)
ANZOLA	81.22	18.78	0.00	3623.80
ARGELATO	91.79	8.21	0.00	3511.71
BARICELLA	88.46	11.54	0.00	4560.12
BAZZANO	0.34	92.27	7.40	1396.17
BENTIVOGLIO	86.35	13.65	0.00	5105.77
BOLOGNA	52.17	44.03	3.80	14069.01
BORGO TOSSIGNANO	82.68	16.41	0.91	2915.22
BUDRIO	89.24	10.76	0.00	12033.21
CALDERARA DI RENO	49.47	48.49	2.04	4125.39
CAMUGNANO	67.56	26.82	5.62	9658.49
CASALECCHIO DI RENO	28.10	60.92	10.98	1737.48
CASALFIUMANESE	86.84	13.01	0.14	8198.27
CASTEL D'AIANO	88.56	11.44	0.00	4524.38
CASTEL DEL RIO	74.89	24.89	0.21	5254.88
CASTEL DI CASIO	77.97	16.40	5.63	4736.48
CASTEL GUELFO	88.64	11.36	0.00	2861.29
CASTEL MAGGIORE	58.71	39.82	1.47	3096.71
CASTEL S. PIETRO TERME	61.72	34.90	3.38	14844.34
CASTELLO D'ARGILE	82.34	17.66	0.00	2906.53
CASTELLO DI SERRAVALLE	85.17	14.60	0.23	3915.96
CASTENASO	84.56	15.44	0.00	3575.25
CASTIGLIONE DEI PEPOLI	71.87	27.89	0.24	6586.26
CRESPELLANO	56.29	43.71	0.00	3783.95
CREVALCORE	92.47	7.53	0.00	10256.05
DOZZA	12.48	86.01	1.51	2421.63
FONTANELICE	87.07	12.93	0.00	3659.37
GAGGIO MONTANO	87.31	12.69	0.00	5868.17
GALLIERA	88.26	11.74	0.00	3714.86
GRANAGLIONE	78.99	18.82	2.19	3957.77
GRANAROLO	91.51	8.49	0.00	3438.51
GRIZZANA	83.44	16.56	0.00	7744.68
IMOLA	60.49	36.60	2.91	20504.03
LIZZANO IN BELVEDERE	83.53	15.67	0.80	8551.54
LOIANO	95.33	4.67	0.00	5238.77
MALALBERGO	79.22	20.78	0.00	5383.39
MARZABOTTO	67.17	31.44	1.39	7452.09
MEDICINA	80.24	19.76	0.00	15910.65
MINERBIO	89.24	10.76	0.00	4306.99
MOLINELLA	71.64	28.36	0.00	12791.60
MONGHIDORO	88.24	11.74	0.02	4813.49
MONTE S.PIETRO	83.53	16.33	0.14	7470.78
MONTERENZIO	92.98	7.02	0.00	10537.49
MONTEVEGLIO	59.22	34.24	6.54	3258.23
MONZUNO	87.81	12.17	0.01	6499.62
MORDANO	90.15	9.85	0.00	2143.36
OZZANO	68.09	31.91	0.00	6476.64
PIANORO	89.65	10.26	0.09	10717.81
PIEVE DI CENTO	66.95	33.05	0.00	1588.79
PORRETTA TERME	59.13	33.35	7.52	3392.41
S.AGATA BOLOGNESE	95.49	4.51	0.00	3478.62
S.BENEDETTO VAL DI SAM	70.28	28.35	1.37	6662.99
S.GIORGIO DI PIANO	100.00	0.00	0.00	3043.85
S.GIOVANNI IN PERSICET	90.64	9.36	0.00	11439.66
S.LAZZARO DI SAVENA	27.18	58.13	14.69	4470.66
S.PIETRO IN CASALE	99.49	0.51	0.00	6587.21
SALA BOLOGNESE	59.72	40.07	0.20	4510.65
SASSO MARCONI	65.15	30.73	4.12	9646.07
SAVIGNO	92.61	7.39	0.00	5487.76
VERGATO	87.21	12.77	0.02	5994.29
ZOLA PREDOSA	45.29	51.00	3.71	3774.95
Total	76.40	22.24	1.36	370216.05

Through the topological overlay of vulnerability map of fig. 3.4 with map of municipality borders in ArcView3.2, it has been possible to calculate their extension for each vulnerable area. This result is obtained using the union tool of the GeoProcessing Wizarz of Arcview3.2. This operation combines features of an input theme with the polygons from an overlay theme to produce an output theme that contains the attributes and full extent of both themes. Before applying this tool, maps must be converted in vector format with the appropriate converting tool. Results are shown in table 3.10. Only 1.36 % of the province is classified as highly vulnerable, 22.24 % as moderate and the major part, 76.40 %, with a low vulnerability. Casalecchio and San Lazzaro showed the highest extensions of vulnerable lands, 10.98 % and 14.69 %, respectively, representing anyway a small portion of the municipal extension and of course of the whole province. Lots of municipalities are with a low vulnerability for almost the entire extension, e.g. San Giorgio di Piano showed 100 % of land classified with a low vulnerability.

Crop allocation for minimizing fresh water toxicity risks

Land vulnerability map to freshwater toxicity can be used to distribute crop in order to minimize their impact in the territory. To do this, it is necessary to integrate the impact value of freshwater toxicity calculated using LCA, and reported in table 3.11, with the site-specific vulnerability. As also described in the Baseline Principle chapter, one method is to calculate an allocation risk value, referring to the different allocation scenarios, defined by a given crop when located in a given vulnerable land, for each crop and for each pixel of the vulnerability map. The freshwater toxicity LCA impact value of each crop was combined with the land vulnerability and weighted on the worst allocation scenario (maize in the most vulnerable areas).

Table 3.11. Allocation risk values of crop - land vulnerability combinations related to freshwater toxicity. FWT is expressed as equivalent phosphate ions (PO_4^{3-} eq.) and as percentage of the highest impacting crop (maize). Impact scores are weighted on the most impacting scenario, i.e. maize when located in high vulnerability lands.

Crop	FWT 1,4-DC eq. (kg ha^{-1})	%	low	moderate	high
maize	**199**	**100.0**	3	6	10
f sorghum	128.0	64.3	1.93	3.86	6.43
rapeseed	101.0	50.8	1.52	3.05	5.08
wheat	99.1	49.8	1.49	2.99	4.98
sunflower	90.5	45.5	1.36	2.73	4.55
miscanthus	76.9	38.6	1.16	2.32	3.86
cynara	74.3	37.3	1.12	2.24	3.73
giant reed	73.9	37.1	1.11	2.23	3.71
switchgrass	50.3	25.3	0.76	1.52	2.53

In particular, to the worst allocation scenario was assigned a value of 10, 6 when maize is located in the moderate vulnerable lands and 3 when is located in a low vulnerable land. Allocation risk of all crops were then referred to maize values. For example, in the case of rapeseed when located in the high vulnerable lands, the calculation were as following:

$$50.8 / 100 \times 10 = 5.08$$

where 50.8 is the eutrophication impact of rapeseed weighted on maize, the most impacting crop, and 10 the allocation value of maize when located in the highest vulnerable areas (table 3.11).

Equally, to calculate the allocation risk of rapeseed in the moderate vulnerable areas the formula will be:

$$82.9 / 100 \times 6 = 3.05$$

Above operation repeated for each crop-vulnerable land combination results in values summarized in table 3.11. Crops allocation risk for each vulnerable area can be mapped, the allocation risk level is defined classifying values of table 3.11 in 3 classes, which ranges are again defined referring to maize scenarios. The values reported in table 3.11 were then polled into three classes and finally mapped (fig. 3.5).

Sorghum and maize showed a very similar allocation risk, as well as for rapeseed, but this last without showing the high allocation risk. Sunflower, wheat, cynara, miscanthus and giant reed showed an allocation risk classified as moderate, respect to maize, only in high vulnerable lands. While switchgrass showed a low impacting risk in all vulnerable lands (fig. 3.5**)**.

The aforementioned information could be summarized in a general map (fig. 3.6) showing the optimal crop allocation from the environmental point of view, minimizing freshwater toxicity, in this case.

Once the land vulnerability is understood and the different crops characterized in term of their allocation risk, one can allocate the more impacting crops in the less vulnerable areas and *vice versa*. In fig. 3.6 it is shown for each vulnerability area which crop may be cultivated. For the lower vulnerable areas all crops might be grown, while, at the opposite, for the higher vulnerability areas only switchgrass presented a low allocation risk, thus being cultivated. In the hypothesis of a district completely dedicated to energy crops, the lowest risk scenario to freshwater toxicity would include only switchgrass. Sunflower, wheat, cynara, miscanthus and giant reed could be grown in low and moderate vulnerable lands as they showed a low allocation risk for that areas (fig. 3.6**).**

Referring information on crop allocation reported on the map of fig. 3.6 to table 3.10, reported percentages also indicate the land portion for each municipality where a given crop may be grown. For example in the municipality of San Lazzaro, 14.69 % of the total extension should not be grown with maize, which it should be grown only in the 28.10 % of the lands. Of course this percentages should be decreases of not agricultural lands portion and/or of other limitations to its cultivation.

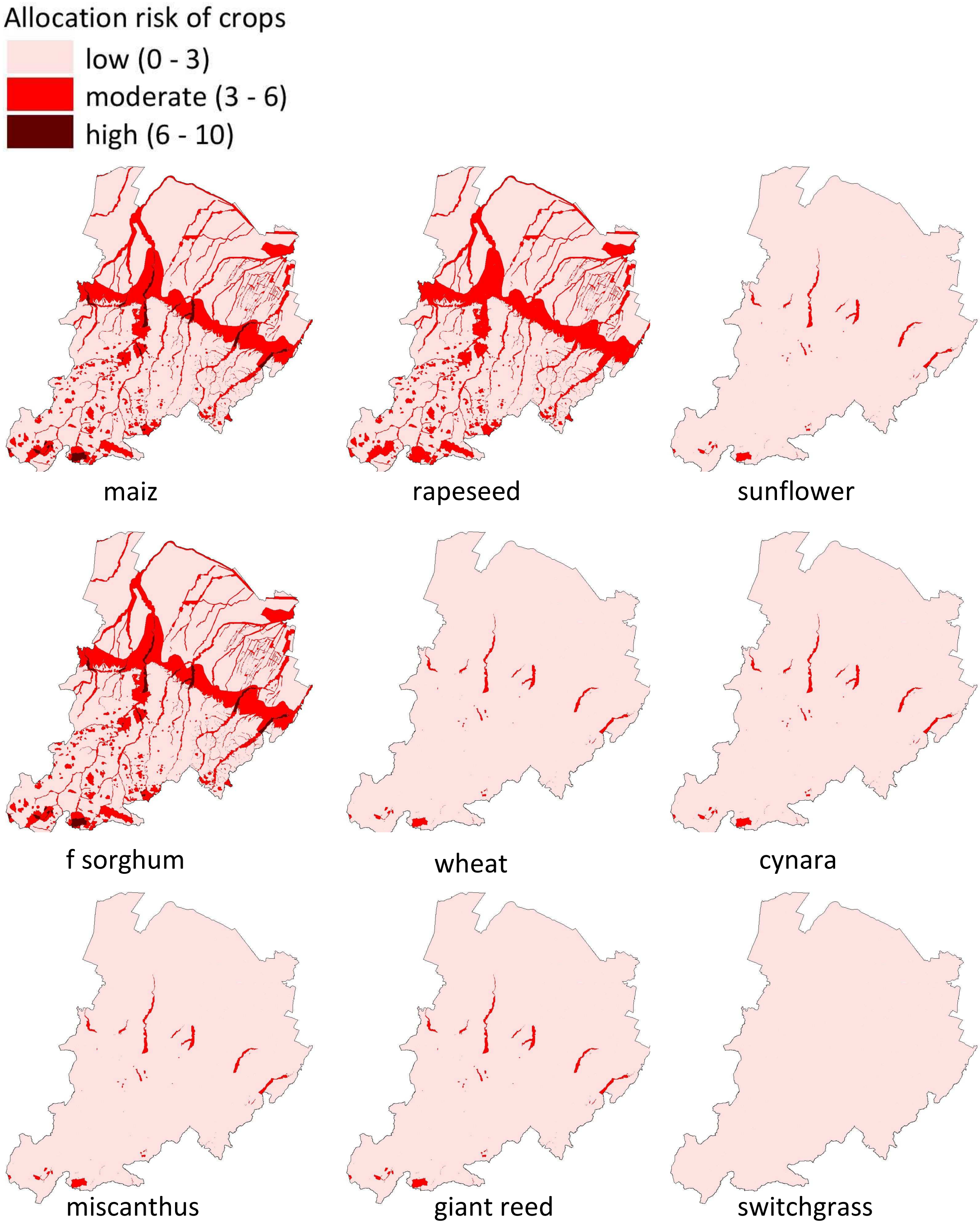


Figure 3.5. Land vulnerability to freshwater toxicity (FWT): allocation risk of crops as classified in 3 classes (low, moderate and high).

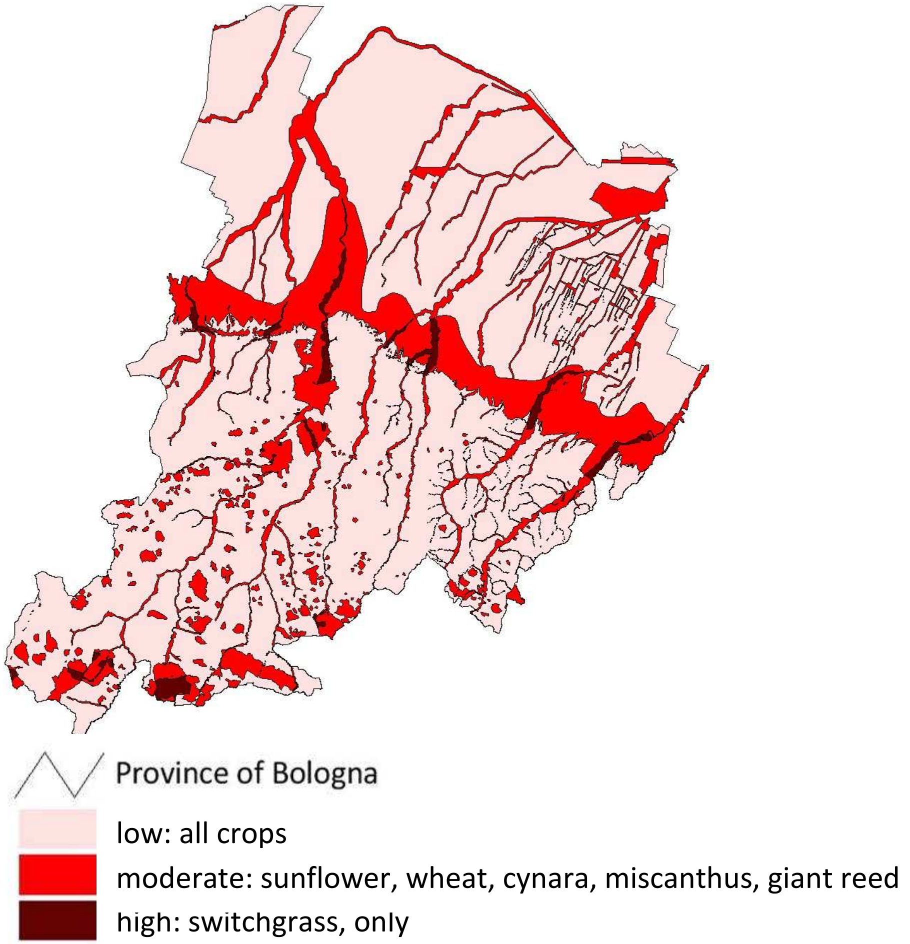


Figure 3.6. Optimal crop allocation to minimize the freshwater toxicity risks (FWT). Low, moderate and high vulnerabilities areas are the same as in fig. 3.4.

Links between eutrophication and freshwater toxicity in the vulnerability definition

The vulnerability to eutrophication and to freshwater toxicity in both cases are linked to the need of protect waters (same target).

The eutrophication is among the more impacting steps in the agricultural production chains and it is mainly linked to the use of fertilizers (Brentrup, Kusters et al. 2004). The toxicity to fresh water, instead, is mainly related to the use of chemicals and pesticides for weed and disease control. When defining the vulnerability and then allocating crops basing on it, it is important to consider both of them, in order to maintain the possibility to discriminate the impacts of crop production chains on the base of the amount of fertilizers and chemicals. A crop production chain that requires large amount of fertilizer, not necessarily require as well as large quantities of chemicals, and vice versa. Several environmental factors that are considered in the definition of the vulnerability map are similar for eutrophication and for freshwater toxicity, because in both cases the target is in general to protect groundwater and water sources, and also the environmental components that are directly or indirectly linked with them (soil, rivers, surface gravels, etc.).

The use of both impacts, eutrophication and freshwater toxicity, increases the overall sustainability when allocating crops basing on their impacts. At the same time, however, there is the risk of double counting for some environmental components and then to overestimate the overall vulnerability for some locations. Several environmental factors may be reasonably used to define both eutrophication and freshwater toxicity vulnerabilities. To avoid overestimation it is very important to try to assign all this factors between the two impacts trying to avoid double counting. As a general rule, for the vulnerability to freshwater toxicity, the environmental factors directly linked with the recharge of drinkable water may be considered, while for the vulnerability to eutrophication, factors linked with the quality of the water in general, also of the ones not directly used for human consumption may instead be used.

Setting up land vulnerability map to eutrophication

The eutrophication effect refers to the overgrow of organisms due to extreme release of nutrients. One main effect is on water, reducing the oxygen concentration and thus the maintaining of biodiversity. Also the effect on nitrate content in waters, that has to be lower that 50 mg nitrate per litre, is of course affected by fertilizers uses. The agricultural use of fertilizer are among the main reasons. The emission of mineral coming from agricultural mainly involved in eutrophication are nitrogen and phosphate (N and P) in the form of nitrates and phosphates use in agriculture. Nitrates and phosphates may reach groundwater through leaching and runoff (Biewinga and Van der Bijl 1996). Nitrates are quite movable through the soil section, phosphate are quite well captured by soil, anyway runoff losses contribution are quite important for eutrophication of surface water (Biewinga and Van der Bijl 1996).

Basing on this aspects, the vulnerability map to eutrophication should consider the presence of rivers and lakes, soil characteristics, as texture, that may affect the nutrient leaching, nitrate effect on waters, soil morphology, agricultural use of fertilizers and their nutrient balance, rainfall pattern, etc.. In practice, the vulnerability map to the eutrophication has been defined mainly in agreement with the methodology indicated in the Plan for Water Protection (Severi, Berrè et al. 2002). Again, in this document, which in most of the parts also were the reference for the definition of the vulnerability to the freshwater toxicity, defined procedures followed an approach that well fit with the concept of land vulnerability to eutrophication. In the framework of this

Protection Plan, several map layers were analysed in order to build the Regional Map of Vulnerability to Nitrate (Determination n. 6636 of 6/7/2011 of the Environment, soil and coast protection Office of the Emilia-Romagna region – Determina n. 6636 del 6/7/2001 della Direzione Ambiente e Difesa del SUolo e della Costa della Regione Emilia-Romagna). The aim however was to split the territory of the region in "vulnerable" and "non-vulnerable areas" including in the first ones, because of their hydrogeological characteristics, the areas in which there is a risk of nitrate pollution of groundwater by the use of agriculture manure and other nitrogen fertilizers. The used methodology took into account climatic and geological characteristics related to the use of land from agriculture (e.g. map of roof gravel from ground level and the map of the degree of protection of the system soil-crop-climate).

Synthetically, this vulnerability map has been created by identifying the areas affected by the presence of gravels at a depth below 10 m from the ground level. In the identification of this areas, soil characteristics were also considered, together with the climate and the type of crop. Finally, zones in which the soil properties preclude or inhibit the flow of water to bottom where also identified. The map thus defines vulnerable areas of the region, from which the information at the provincial level was extracted, with the presence of polluted water or susceptible to pollution by nitrates from agricultural sources. The effect of the soil texture and the presence of gravel and sand on the leaching was also considered, as well as the amount of nitrate from agricultural activities in groundwater, in order to identify where the presence is already high and then deserving a major protection. The topological overlay of all this maps brings to the definition of the vulnerable lands to nitrates showed in fig. 3.7, and it represents the areas of the Province where groundwater are polluted of susceptible of pollution of nitrate from the agricultural activities. Further details on the production of this vulnerability map to nitrates are contained in the document "Technical details on the production of the New Regional Vulnerability Map: methodological aspects (Severi, Berrè et al. 2002).

Figure 3.7. Vulnerable areas to nitrates in the province of Bologna, extracted from the regional map.

Vulnerable areas are mainly located at the central area of the province, corresponding with the beginning of the flat fertile lands. 10.95 % (40524.95 ha) of the total province extension has been classified as vulnerable to nitrates.

However, there is an overlap with those of environmental variables used in the map of vulnerability to freshwater toxicity, for example, this vulnerability map to nitrates has been used, together with the hydrogeological characteristics mentioned in the previous chapter, for the definition of the external borders of Type B areas of the "Groundwater protection areas in foothill and lowland territories ".

Other land characteristic were also added to the vulnerability to nitrates, as identified in fig. 3.7, and in particular the soil texture map, in order to emphasize the texture variation of the flat area (northern part of the map), and the river valley maps, in order to avoid the cultivation of high releasing nitrogen crop in these areas. With all mentioned environmental layers, the agricultural use of the land were emphasized, while all land factors linked to the conservation of the water quality, and mainly referring to its potability, were only used in the definition of the land vulnerability map to freshwater toxicity.

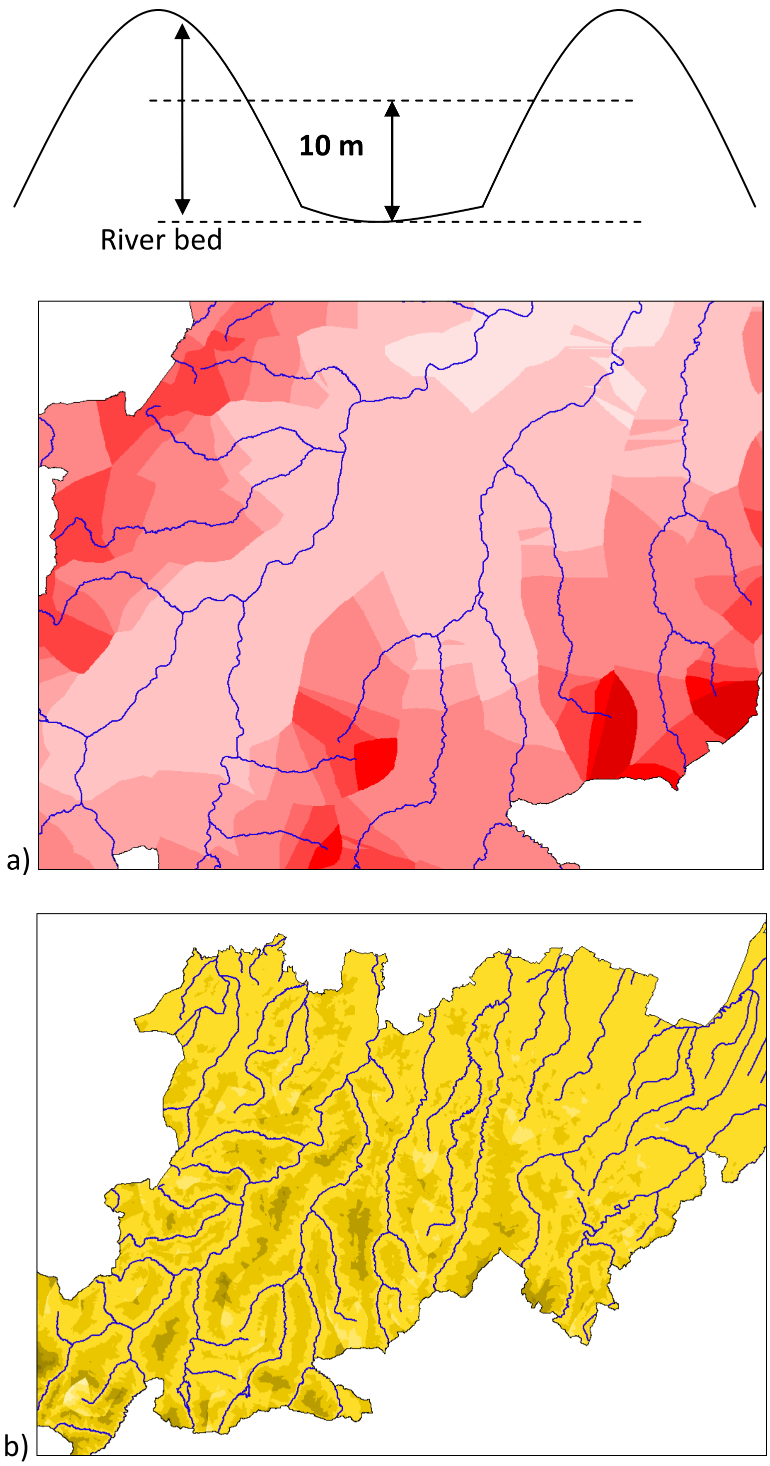


Figure 3.8. Steps for river valley map production. a) Proximity map. Different colours represents different altitude values. b) Differential overlay map between proximity map and terrain altitudes.

Soil map 1:250000 with texture data is available from the geographic data catalogue of the Province of Bologna (http://cst.provincia.bologna.it:81/catalogo/).

Map of river valleys were not available, thus it was elaborated within ArcView3.2 using several base layers. Followed procedure is briefly listed below:

1. Rivers maps (polylines) converted in Rivers maps (points)
2. Attribution to each point of the altitude value after their overlay with the Digital Elevation Model of the Province.
3. Assign proximity tool of ArcView3.2. the result is a raster map where each pixel results in the nearest value of point's altitude (fig. 3.8a).
4. Differential overlay between the DEM with proximity map of fig. 3.8b)
5. Selection of pixels where the difference is lower than 10 m (Fig. 3.9)

Most of rivers are located between 7 and 203 m a.s.l.. In total, valley extension resulted 3671 ha.

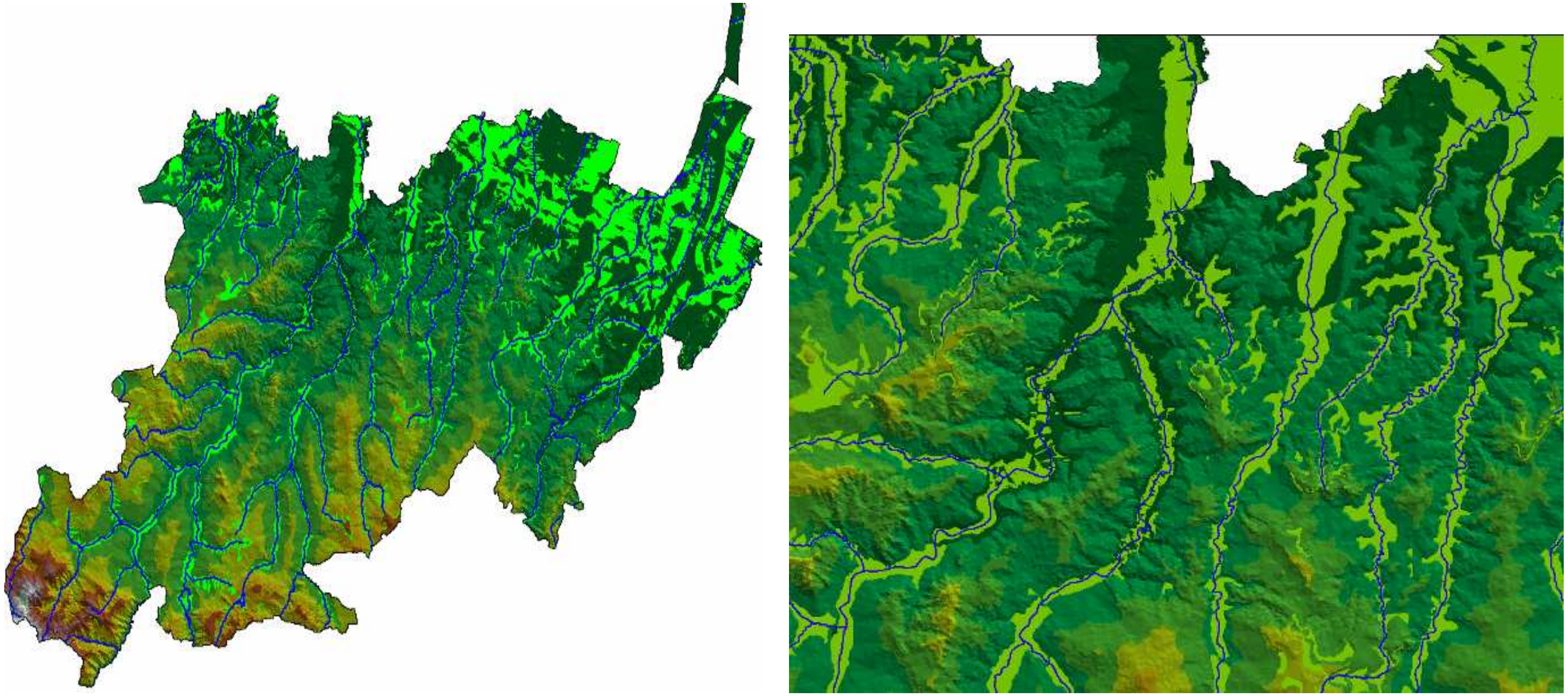


Figure 3.8. Map of river valleys in the Province of Bologna on DEM. Flat area in the Northern part is not considered.

Finally, all environmental layers used to define the vulnerability map to eutrophication, and the attributed vulnerability score, are listed in the table 3.12. They involve the vulnerability map to nitrates, wet areas and river valleys (from the land use map and from the elaboration of river way and land morphology), and the soil map, with attribution of a vulnerability score basing on the main texture. Each map's attribute reached a vulnerability score ranging from 1 to 4. This score assignment remains quite subjective, even if it may be supported by reliable principles: soil with fine texture is less vulnerable to eutrophication because of its ability in leaching limitation. In this phase, specific skills on eutrophication problems are particularly required.

Table 3.12. Vulnerability score of map attributes used to define vulnerability to eutrophication (low=1; high=4).

Land map	Map attribute	Vulnerability score
Vulnerability map to nitrates	Vulnerable areas	4
Wet areas. Low lands generally flooded during winter or covered by water during all seasons. Riverbeds with vegetation. River valleys and wet areas (from the Land use Map 2003 of the Emilia Romagna Region)	Wet areas	3
Soil map 1:250000 from the Emilia Romagna Region Information service	fine texture	1
	medium texture	3

Score were added for each map attribute in the attribute table as a new column called "addvuln" (summands of vulnerability). Before overlaying, all maps where converted in raster format and reported at the same resolution, fixed at 50 m each pixel. The pixel of 50 m consequently also identifies the minimum level of analysis. Produced raster maps have been overlaid and using “map calculator” tool of the GIS software Arcview3.2, all vulnerability scores were summed pixel by pixel.

The resulting map is showed in fig. 3.9, which shows the vulnerable areas in the Province of Bologna, and fig. 3.10 where the vulnerability has been classified in low, moderate and high, following the equal area approach. Each pixel in fig. 3.9 is the sum of all the single scores associated to each variable.

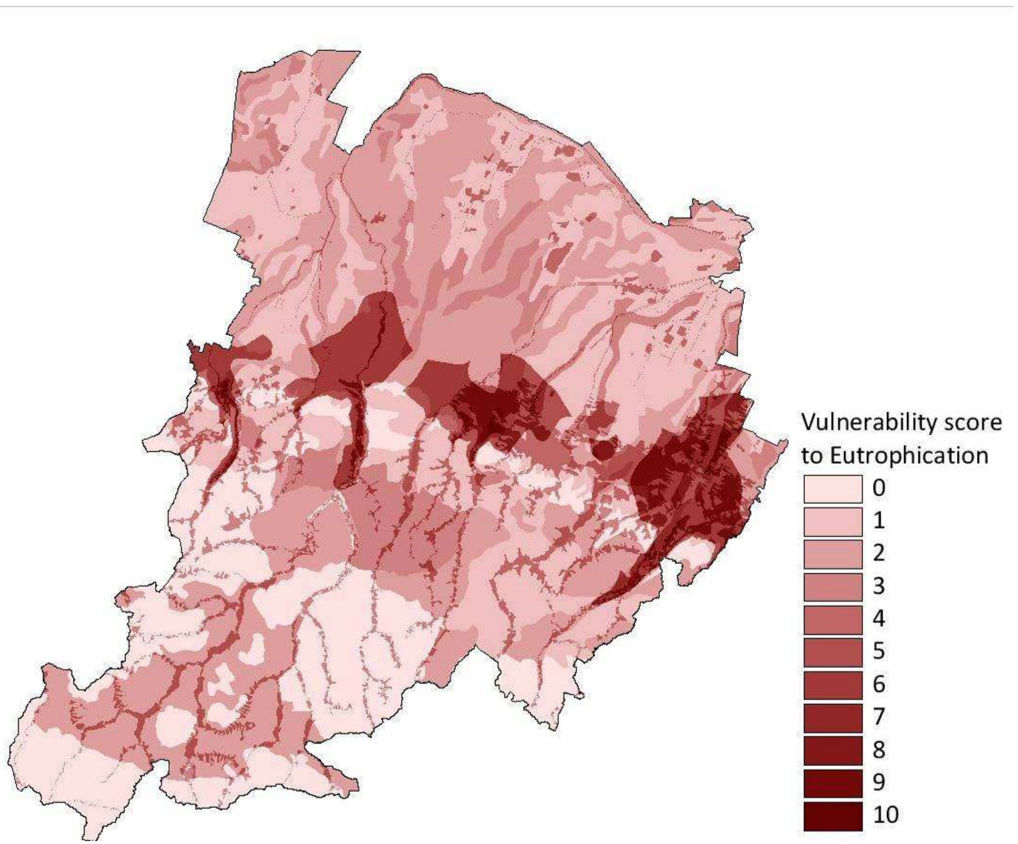


Figure 3.9. Vulnerability map to eutrophication (EU). This map is the result of the topological overlay of the land maps listed in table 3.12 (increasing vulnerability to eutrophication from 0 to 10).

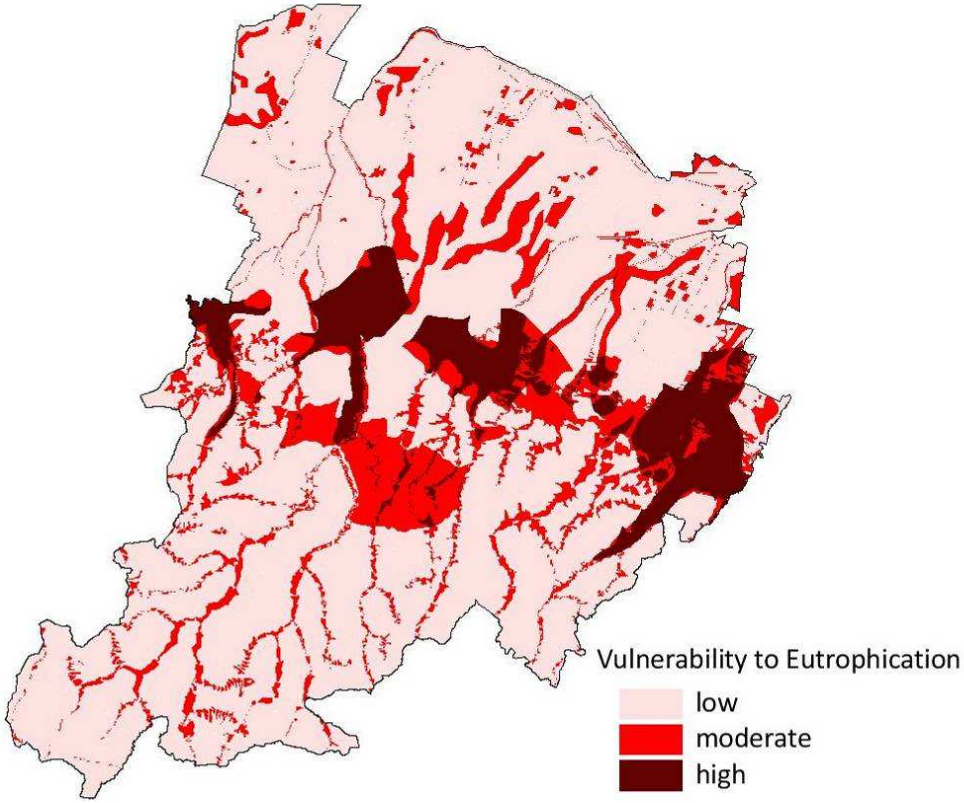


Figure 3.10. Classified vulnerability map to eutrophication (EU) based on equal area method.

The vulnerability ranged from 0 to 10 (fig. 3.9). The differences in the flat areas (Northern part) are mainly due to soil texture, while differences in the Southern part are mainly caused by river valleys and soil texture. Most vulnerable areas located in the centre of the map are mainly due to the presence of vulnerable lands to nitrates. This area are at the end of the sloping areas of Apennines. Some parameter such as slope, rainfall, or water table depth, that may further affect the vulnerability to eutrophication, were already included within the vulnerability map to nitrates by the Regional Office of Water Protection.

The area was divided into 3 classes of vulnerability basing on equal areas approach. Insignificant areas smaller than 1 ha were eliminated. The map was converted into vector format for an easier layout (fig. 3.10).

The final output was that 73.91 %, 17.36 % and 9.73 % of the whole province extension (almost 370.000 ha) were recognized as low, moderate and highly vulnerable, respectively.

Bazzano showed the higher portion of his extension (89.67 %) classified with high vulnerability, followed by San Lazzaro and Imola, with their 59.88 % and 57.23 %, respectively, of high vulnerable lands to eutrophication. Higher portion of moderate vulnerable lands is located in Sasso Marconi (46.94 %), while low vulnerable lands are quite homogenously distributed in the flat and hilly area of the province.

Table 3.13. Vulnerability to eutrophication (EU) of municipalities in the Province of Bologna.

Municipality	low (%)	moderate (%)	high (%)	Total (ha)
ANZOLA	92.08	7.92	0.00	3621.75
ARGELATO	78.11	21.75	0.15	3511.70
BARICELLA	91.63	8.37	0.00	4555.79
BAZZANO	3.50	6.82	89.67	1386.62
BENTIVOGLIO	81.29	18.71	0.00	5105.76
BOLOGNA	47.53	7.38	45.09	14069.01
BORGO TOSSIGNANO	81.19	6.97	11.84	2908.41
BUDRIO	78.68	20.86	0.46	12033.21
CALDERARA DI RENO	69.31	4.73	25.96	4125.39
CAMUGNANO	85.39	14.61	0.00	9652.65
CASALECCHIO DI RENO	39.25	15.06	45.69	1737.48
CASALFIUMANESE	80.85	15.54	3.60	8198.27
CASTEL D'AIANO	90.67	9.33	0.00	4514.23
CASTEL DEL RIO	94.73	5.27	0.00	5234.46
CASTEL DI CASIO	86.98	13.02	0.00	4732.35
CASTEL GUELFO	91.33	1.20	7.48	2861.29
CASTEL MAGGIORE	45.48	40.81	13.71	3096.71
CASTEL S. PIETRO TERME	51.93	38.02	10.05	14844.34
CASTELLO D'ARGILE	95.80	4.20	0.00	2906.38
CASTELLO DI SERRAVALLE	66.26	24.78	8.96	3911.57
CASTENASO	70.88	4.70	24.42	3575.25
CASTIGLIONE DEI PEPOLI	91.24	8.76	0.00	6572.01
CRESPELLANO	72.43	13.75	13.82	3782.45
CREVALCORE	81.48	18.46	0.06	10237.30
DOZZA	26.97	32.30	40.72	2421.63
FONTANELICE	90.47	9.53	0.00	3653.18
GAGGIO MONTANO	88.11	11.89	0.00	5863.44
GALLIERA	94.98	5.02	0.00	3704.89
GRANAGLIONE	95.42	4.58	0.00	3916.62
GRANAROLO	75.46	24.54	0.00	3438.51
GRIZZANA	89.79	10.21	0.00	7744.67
IMOLA	25.66	17.12	57.23	20455.86
LIZZANO IN BELVEDERE	95.01	4.99	0.00	8538.27
LOIANO	80.05	18.51	1.44	5238.77
MALALBERGO	87.46	12.54	0.00	5378.93
MARZABOTTO	89.66	10.31	0.03	7452.08
MEDICINA	82.02	17.60	0.39	15908.26
MINERBIO	62.17	37.83	0.00	4306.99
MOLINELLA	86.45	13.41	0.14	12765.96
MONGHIDORO	91.41	8.59	0.00	4803.25
MONTE S.PIETRO	71.23	26.55	2.23	7470.77
MONTERENZIO	88.77	10.90	0.34	10533.91
MONTEVEGLIO	49.77	28.23	22.00	3255.96
MONZUNO	79.56	19.72	0.72	6499.62
MORDANO	63.18	31.38	5.44	2133.63
OZZANO	31.05	35.58	33.37	6476.63
PIANORO	31.07	61.72	7.20	10717.79
PIEVE DI CENTO	72.46	27.54	0.00	1581.83
PORRETTA TERME	91.16	8.84	0.00	3392.28
S.AGATA BOLOGNESE	95.85	4.15	0.00	3476.10
S.BENEDETTO VAL DI SAM	91.26	8.74	0.00	6655.97
S.GIORGIO DI PIANO	94.51	5.41	0.08	3043.84
S.GIOVANNI IN PERSICET	97.61	2.39	0.00	11431.13
S.LAZZARO DI SAVENA	17.92	22.21	59.88	4470.65
S.PIETRO IN CASALE	92.14	7.82	0.04	6587.20
SALA BOLOGNESE	95.44	4.56	0.00	4510.64
SASSO MARCONI	39.08	46.94	13.98	9646.06
SAVIGNO	85.77	14.18	0.05	5484.34
VERGATO	82.49	17.51	0.00	5992.89
ZOLA PREDOSA	52.65	19.24	28.11	3774.95
Total	72.91	17.36	9.73	369901.85

Crop allocation for minimizing eutrophication risks

Crops may be distributed integrating LCA eutrophication with the vulnerability maps of fig. 3.10. Distribution may occur calculating an allocation risk value each crop-vulnerable land combination, considering the eutrophication LCA impact values (table 3.14).

Table 3.14. Allocation risk values of crop - land vulnerability combinations related to eutrophication (kg ha^{-1}). EU is expressed as equivalent phosphate ions (PO_4^{3-} eq.) and as percentage of the highest impacting crop (maize). Impact scores are weighted on the most impacting scenario, i.e. maize when located in high vulnerability lands.

Crop	EU PO_4^{3-} eq. (kg ha^{-1})	%	low	moderate	high
maize	**5.56**	**100**	**3**	**6**	**10**
rapeseed	4.61	82.9	2.49	4.97	8.29
sunflower	4.46	80.2	2.41	4.81	8.02
sorghum	4.38	78.8	2.36	4.73	7.88
wheat	4.37	78.6	2.36	4.72	7.86
cynara	1.85	33.3	1.00	2.00	3.33
miscanthus	1.67	30.0	0.90	1.80	3.00
giant reed	1.64	29.5	0.88	1.77	2.95
switchgrass	1.37	24.6	0.74	1.48	2.46

The eutrophication effect of each crop was combined with the land vulnerability and weighted on the worst allocation scenario (maize in the most vulnerable areas). For example, in the case of rapeseed the calculation were as following:

$$82.9 / 100 \times 10 = 8.29$$

where 89.2 is the eutrophication impact of rapeseed weighted on maize, the most impacting crop, when located in the highest vulnerable areas (table 3.14). Equally, to calculate the score of rapeseed in the moderate vulnerable areas the formula will be:

$$82.9 / 100 \times 6 = 4.97$$

Above operation repeated for each crop-land allocation result in values summarized in table 3.14.

Crops may be distributed in the different areas basing on this calculated allocation risk value. The values reported in table 3.14 were then polled into three classes and finally mapped (fig. 3.11).

Maize showed important eutrophication risk in all areas. Rapeseed, wheat, sunflower and fibre sorghum showed similar risks to maize (fig. 3.11). Giant reed, miscanthus and switchgrass revealed much lower impacts than maize at each vulnerability class. Cynara showed a risk classified as moderate only in the high vulnerability areas in the centre of the Province (fig. 3.11).

The aforementioned information could be summarized in a general map (fig. 3.12) showing the optimal crop allocation from the environmental point of view (eutrophication in this case).

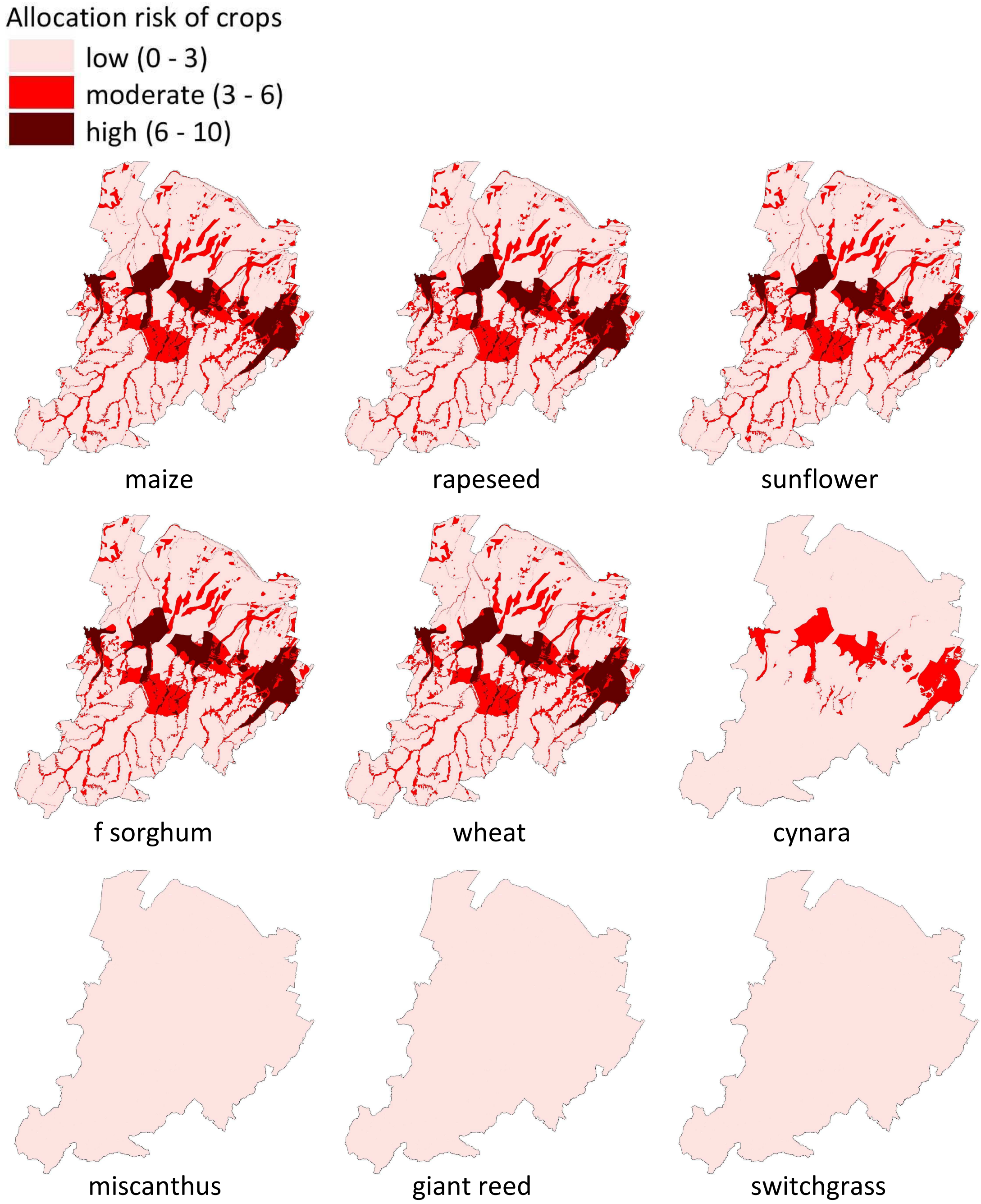


Figure 3.11. Land vulnerability to eutrophication: allocation risk of crops as classified in 3 classes (low, moderate and high).

Once the land vulnerability is understood and the different crops characterized in term of their impacts (eutrophication in this example), one can allocate the more impacting crops in the less vulnerable areas and *vice versa*. In fig. 3.12 it is shown for each vulnerability area which crop may be cultivated. For the lower vulnerable areas all crops might be grown, while, at the opposite, for the higher vulnerability areas only giant reed, miscanthus and switchgrass may be cultivated.

In the hypothesis of a district completely dedicated to energy crops the lowest risk scenario to eutrophication would include only giant reed, switchgrass and miscanthus, all perennials. Therefore, if the eutrophication is considered a major concern, maize should be grown only in the low vulnerability areas (fig. 3.12).

Moving information on crop allocation of fig. 3.12, to table 3.13, reported percentages in the table also indicate the land portion for each municipality where a given crop may be grown. For example in the municipality of Imola, 57.23 % of the total extension should not be grown with maize, that it should be grown only in the 25.66 % of the lands. Of course this percentages should be decreases of not agricultural lands or other limitations linked with the crop cultivation.

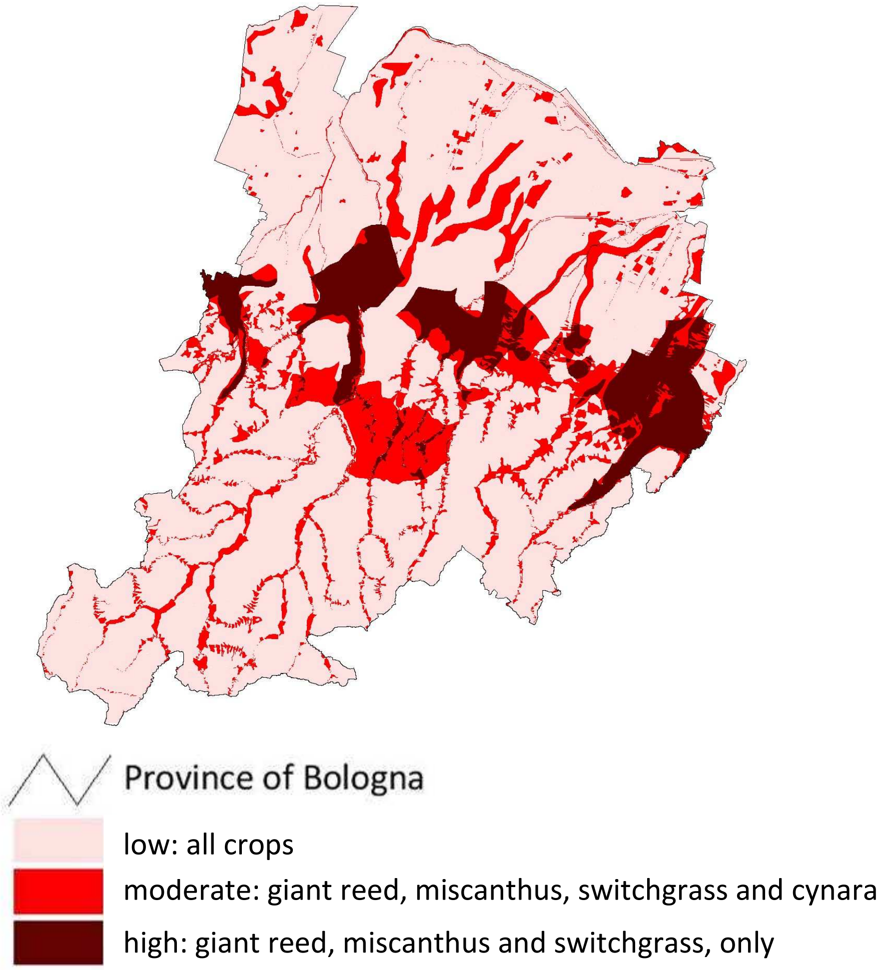


Figure 3.12. Optimal crop allocation to minimize the eutrophication (EU) risks. Low, moderate and high vulnerabilities areas are the same as in fig. 3.10.

Setting up land vulnerability map to human toxicity

The human toxicity is expressed as kg ha^{-1} of 1,4-dichlorobenzene equivalent and it has been calculated with the USES-LCA procedure, that takes in consideration the fate, the exposure and the effect of several toxic substances to exposed persons for a indefinite time horizon (Monti, Fazio et al. 2009).

Among the various components that contribute to define the human toxicity there are metals and fine particles that fall into the ground, or, when emitted into the air they can fall not far from the source. For the definition of the vulnerability map of to human toxicity, the approach of “proximity to the target” it can be followed. The target can be identified with the presence and the extension of urban areas. This approach then brings to the definition of the deposition distance of pollutants from the source and then the presence of the target. This could depends on several factors such as speed and direction of prevailing winds, surface roughness, which determines the turbulent motions, atmospheric stability, morphology of the territory, etc. (Wang, Davis et al. 2006).

The vulnerability map should be then based on the concept of the climatic footprint for each of urban area, i.e. gas/particle emission footprint map of urban areas, which defines where potentially emission sources, which emissions are able to reach urban areas, can be located (Wang, Davis et al. 2006). Vulnerable areas can be imaged as a sort of buffer around the urban agglomeration. Where there is an intersection of more than one buffer, the vulnerability is higher, because a potential emission source that is there located would reach more that one target.

Basing on this approach this map is hard to define because lot of information about predominant wind direction, surface roughness, etc. and skills on atmospheric physics are needed.

The population density also can be related to vulnerability, e.g. high population densities values increase the vulnerability level because of the higher presence of targets per surface unit. The vulnerability map to human toxicity can then be produced considering the proximity criteria and humans as targets. A simple and immediate method to classify the province of Bologna respect to its vulnerability to human toxicity is to calculate the population density map using municipally based resident data from the national statistic data service ISTAT. ISTAT releases information on residents for each municipality, representing then also the higher spatial resolution. Elaborating resident data in ArcView3.2 and linking them with the map of municipalities of the Province with the use of the identification code defined by ISTAT, it was possible to calculate the population density map of the Province.

The higher the density value, the higher the vulnerability. Population values were then classified in three classes of vulnerability, fig. 3.13 shows the resulting map. Population density resulted very variable, ranging from 21.71 persons km^{-2} to a maximum of 2651.4 persons km^{-2} (table 3.15).

Values were aggregated in 3 classes, thus the province was classified as low, moderate and high vulnerable to human toxicity, on the base of an equal area classification approach. In other words, the vulnerability is defined on the base of the variation of the population density, areas with the highest population density reach the highest vulnerability value.

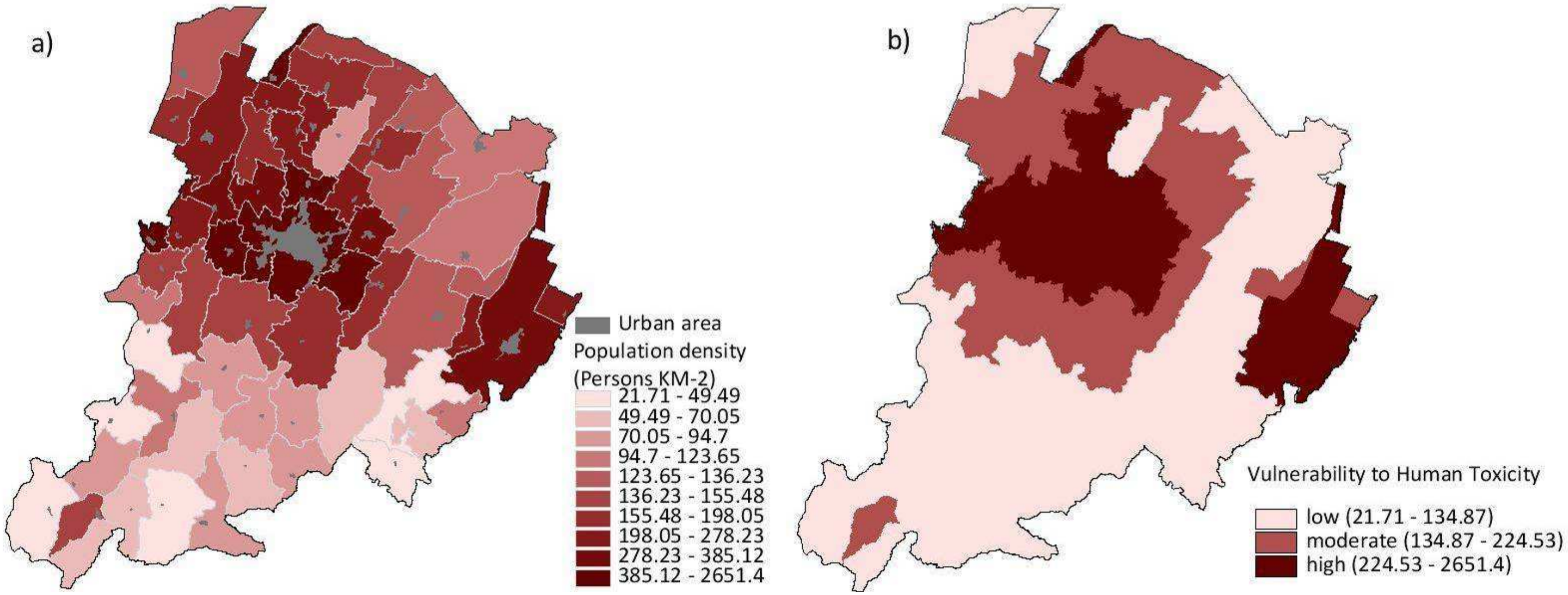


Figure 3.13. Land vulnerability map to human toxicity (a) and classified in 3 classes (low, moderate and high vulnerability) (b). This map has been obtained classifying the area in 3 vulnerability classes based on population density. The higher the population density, the more the vulnerability to human toxicity.

Table 3.15. Vulnerability to human toxicity (HUMT), population density and extension of municipalities in the Province of Bologna.

ISTAT code	Municipality	AREA (Km^2)	Population density (p km^{-2})	Vulnerbility
37001	ANZOLA	36.2380	317.07	high
37002	ARGELATO	35.1171	266.25	high
37003	BARICELLA	45.6012	134.29	low
37004	BAZZANO	13.9617	461.62	high
37005	BENTIVOGLIO	51.0577	94.11	low
37006	BOLOGNA	140.6901	2651.40	high
37007	BORGO TOSSIGNANO	29.1522	110.69	low
37008	BUDRIO	120.3321	136.23	moderate
37009	CALDERARA DI RENO	41.2539	309.55	high
37010	CAMUGNANO	96.5849	21.71	low
37011	CASALECCHIO DI RENO	17.3748	1987.02	high
37012	CASALFIUMANESE	81.9827	39.53	low
37013	CASTEL D'AIANO	45.2438	43.70	low
37014	CASTEL DEL RIO	52.5488	23.86	low
37015	CASTEL DI CASIO	47.3648	70.05	low
37016	CASTEL GUELFO	28.6129	136.09	moderate
37017	CASTELLO D'ARGILE	29.0653	209.39	moderate
37018	CASTELLO DI SERRAVALLE	39.1596	115.37	low
37019	CASTEL MAGGIORE	30.9671	539.48	high
37020	CASTEL S. PIETRO TERME	148.4434	134.87	low
37021	CASTENASO	35.7525	385.12	high
37022	CASTIGLIONE DEI PEPOLI	65.8626	89.52	low
37023	CRESPELLANO	37.8395	233.12	high
37024	CREVALCORE	102.5605	125.01	low
37025	DOZZA	24.2163	248.26	high
37026	FONTANELICE	36.5937	51.05	low
37027	GAGGIO MONTANO	58.6817	85.00	low
37028	GALLIERA	37.1486	150.13	moderate
37029	GRANAGLIONE	39.5777	56.88	low
37030	GRANAROLO	34.3850	278.23	high
37031	GRIZZANA	77.4468	52.20	low
37032	IMOLA	205.0403	325.10	high
37033	LIZZANO IN BELVEDERE	85.5154	26.95	low
37034	LOIANO	52.3877	84.98	low
37035	MALALBERGO	53.8339	151.37	moderate
37036	MARZABOTTO	74.5208	87.89	low
37037	MEDICINA	159.1065	96.33	low
37038	MINERBIO	43.0699	198.05	moderate
37039	MOLINELLA	127.9159	117.73	low
37040	MONGHIDORO	48.1349	80.81	low
37041	MONTERENZIO	105.3749	53.12	low
37042	MONTE S.PIETRO	74.7078	145.66	moderate
37043	MONTEVEGLIO	32.5823	155.48	moderate
37044	MONZUNO	64.9962	94.70	low
37045	MORDANO	21.4336	205.43	moderate
37046	OZZANO	64.7664	182.39	moderate
37047	PIANORO	107.1781	155.59	moderate
37048	PIEVE DI CENTO	15.8879	432.85	high
37049	PORRETTA TERME	33.9241	139.40	moderate
37050	SALA BOLOGNESE	45.1065	169.40	moderate
37051	S.BENEDETTO VAL DI SAM	66.6299	67.61	low
37052	S.GIORGIO DI PIANO	30.4384	241.60	high
37053	S.GIOVANNI IN PERSICET	114.3966	224.53	moderate
37054	S.LAZZARO DI SAVENA	44.7065	676.14	high
37055	S.PIETRO IN CASALE	65.8721	168.57	moderate
37056	S.AGATA BOLOGNESE	34.7862	193.41	moderate
37057	SASSO MARCONI	96.4607	149.49	moderate
37058	SAVIGNO	54.8776	49.49	low
37059	VERGATO	59.9429	123.65	low
37060	ZOLA PREDOSA	37.7495	447.48	high

The maximum resolution corresponds with the municipality extension. Such resolution can represent a weak point of this map, anyway acceptable: municipalities are the lower level of the territory government able to take decisions, thus also the rough approximation to municipal extension can have a sense.

Around 52 % of the total Province extent resulted classified with a low vulnerability class, while 21 % as highly vulnerable.

More densely areas are located in the centre of the map, corresponding with the Bologna’s urban area and on the Eastern part of the map, corresponding with Imola municipality. The southern part of the province has been classified with a low vulnerability. They also are the mountainous portion with the lower population densities of the province.

Crop allocation for minimizing human toxicity risks

Crops can be allocated in the province minimizing the human toxicity risks based on their allocation risk value, following the same procedure for eutrophication and freshwater toxicity. This value can be calculated for each allocation scenario. The allocation scenario in this case is defined by the crop and by one of the three vulnerability classes to human toxicity. Values are calculated respect to scenarios with the highest allocation risk’s values, that correspond to maize (the most impacting crop) when located in highly vulnerable lands (allocation risk = 10). Thus, for rapeseed when located in highly vulnerable areas,

allocation risk = 63.54 (see table 3.16) / 100 * 10 (allocation risk value for maize in highly vulnerable areas).

While for rapeseed when located in low vulnerable lands,

allocation risk = 63.54 / 100 * 3 (that is the allocation risk for maize when located in low vulnerable lands).

Table 3.16. Allocation risk values of crop regards human toxicity (HUMT). % means HUMT respect to maize. Low, moderate and high refer to classes of land vulnerability to human toxicity.

Crop	HUMT 1,4-DC eq. (kg ha^{-1})	%	low	moderate	high
maize	**1810**	**100**	3.0	6.0	10.0
f sorghum	1360	**75.14**	2.3	4.5	7.5
wheat	1180	**65.19**	2.0	3.9	6.5
rapeseed	1150	**63.54**	1.9	3.8	6.4
sunflower	1150	**63.54**	1.9	3.8	6.4
cardoon	738	**40.77**	1.2	2.4	4.1
miscanthus	709	**39.17**	1.2	2.4	3.9
arundo	661	**36.52**	1.1	2.2	3.7
switchgrass	474	**26.19**	0.8	1.6	2.6

Allocation risk values of table 3.16 were then related to the land vulnerability map to human toxicity and mapped for each crop (fig. 3.14).

Maize, rapeseed, wheat, sunflower and sorghum showed a high risk of allocation in all vulnerable lands, while giant reed, cynara and miscanthus generally showed lower impacts. Their allocation risk resulted classified as moderate respect to maize where the vulnerability is high (municipality of Bologna and Imola). Switchgrass showed a negligible risk, classified as low, in the whole province, resulting as the crop that could be grown in the entire territory with a low allocation risk.

Above consideration can be summarized in a map (fig. 3.15) showing possible crop allocations minimizing human toxicity impact.

Central area of the map (fig. 3.15) refers to the urban area of Bologna and Imola. Based on the proposed classification, in this part of the province only switchgrass should be grown, while in moderate vulnerable lands, giant reed, cynara, miscanthus and switchgrass may be grown, as they showed an allocation risk classified as low (fig. 3.14) when located in that areas. The rest of crops (maize, rapeseed, wheat, sunflower and sorghum) should be grown only on low vulnerable lands to human toxicity, in part of the fertile flat valley at the Northern part of the map, e.g. Molinella, Minerbio, Medicina and Castel San Pietro Terme, and in the Apennines area, where population density is lower, but were pedoclimatic constraints may limit their cultivation or decreasing yields.

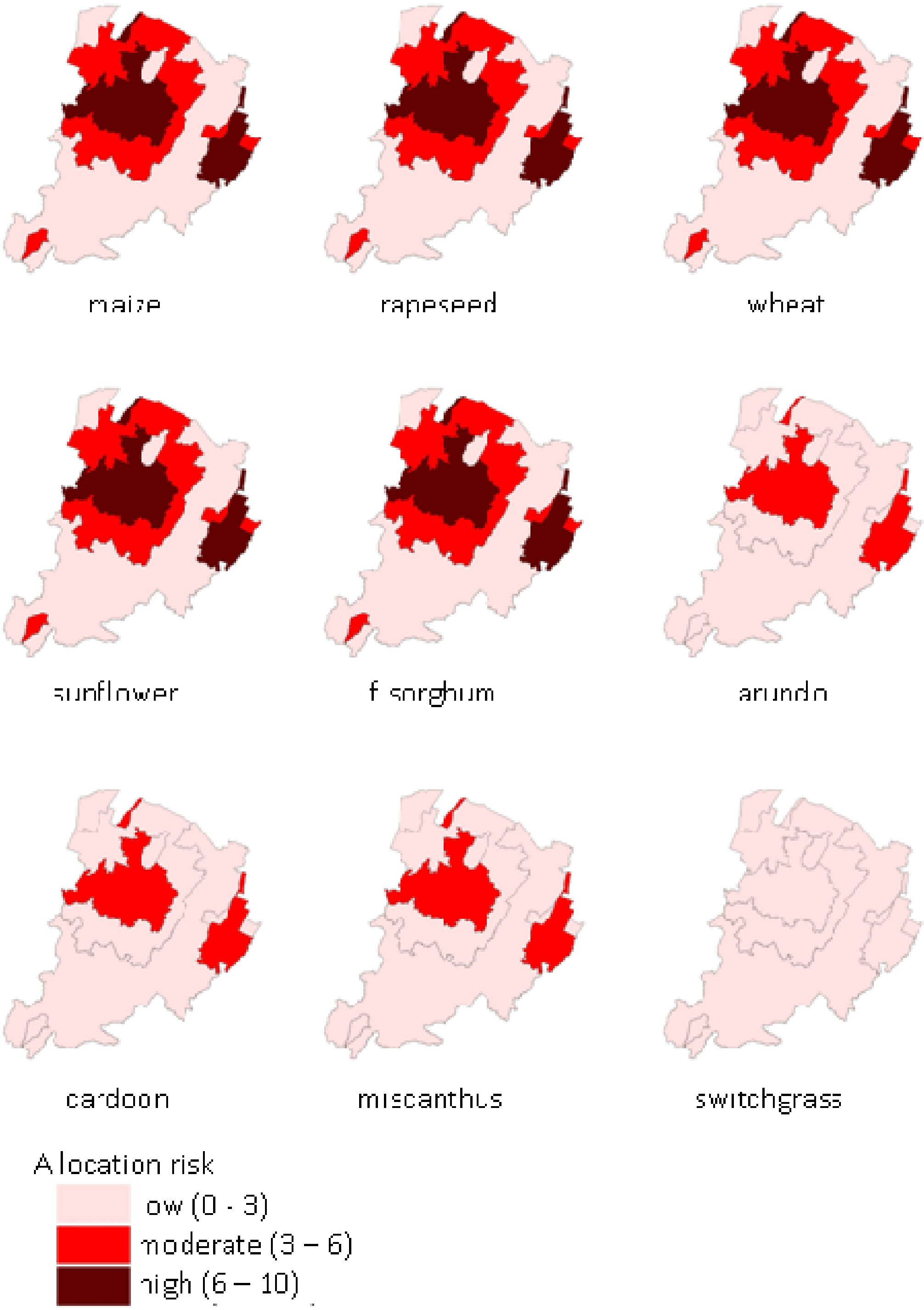


Figure 3.14. Maps of allocation risk to human toxicity for each "crop-vulnerability" area combination.

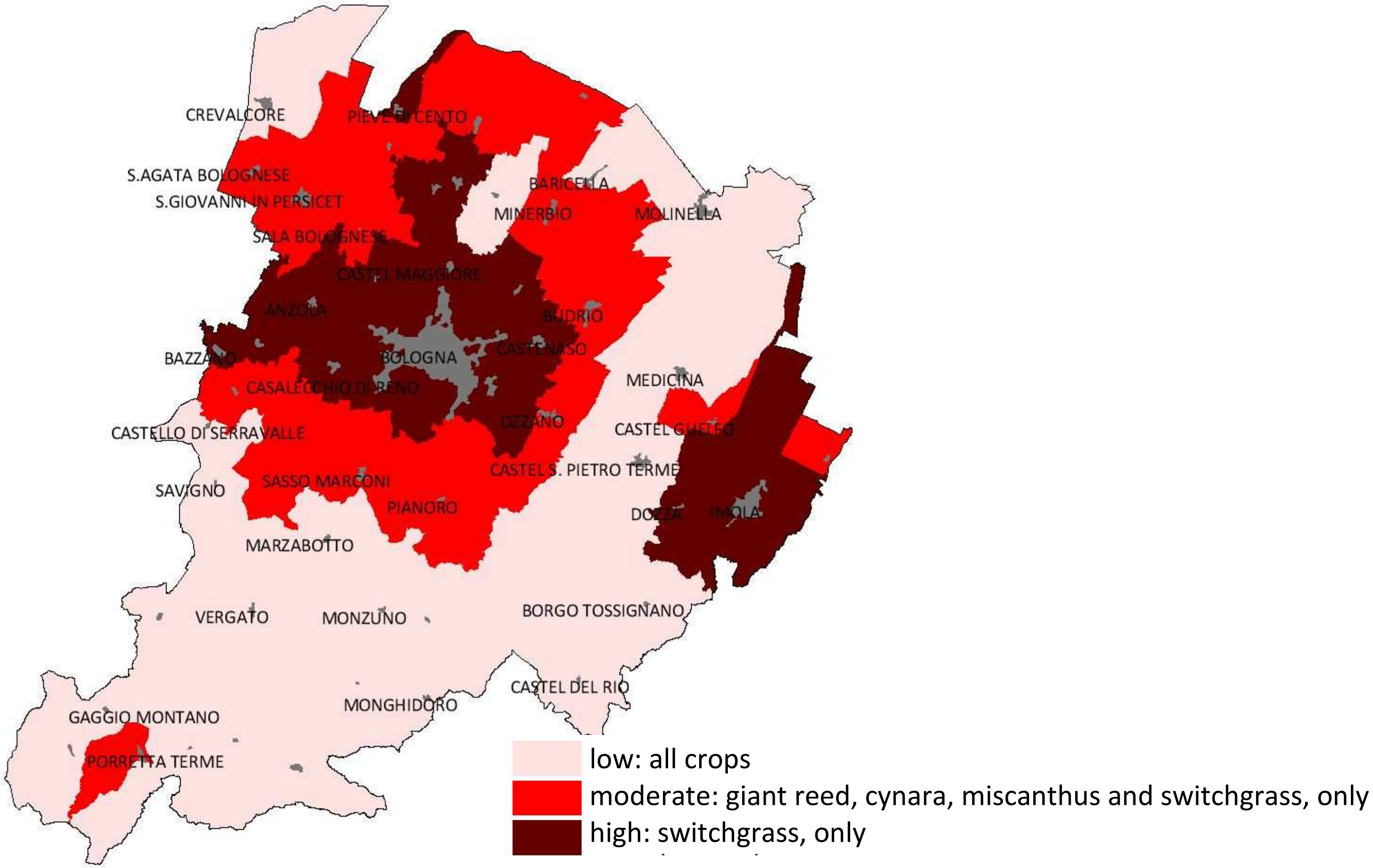


Figure 3.15. Optimal land allocation to minimize human toxicity risks. Low, moderate and high represent vulnerability classes to human toxicity.

4. Methods for crop allocation based on multiple impact indicators

Introduction
Simple additive method and crop allocation
Additive method of classified maps and crop allocation
Composed multiplicative method and crop allocation

Highlights

Environmental impact minimization of the production chain in crop allocation is maximized if it is possible to consider as many as possible impact indicators with local effects. Basically, two methods categories can be defined, i.e. with or without an additional operation of synthesis, that is the calculation of a total impact indicator and of a comprehensive vulnerability map. The distribution of vulnerable lands among municipalities and inside them changed when considering more than one impact indicator, as well as for impacts of crops. It also adds complexity and uncertainty to the method as increasing numbers of classifications and non objective choices. Methods to integrate impacts and vulnerability maps must be well defined and transparent. Compared with optimal allocations considering only one impact indicator, it is still more evident that only switchgrass can be cultivated in high vulnerability lands. The CMM well suits the possibility to use more than two impact indicators with local effect.

Introduction

Crop allocation in the territory taking into account the impact minimization of the production chain to the environment is maximized if it is possible to consider at the same time as many as possible impact indicators with local effects, as already introduced in last paragraph of chapter 2 baseline principles. To integrate more than one impact indicator it could means to calculate a “total impact index” that in a sort of way summarize all impacts with local effect that are used. The definition of this total indicator could follow several approaches that wants to compare variables with different units and of different orders. In table 3.7 of chapter 3, also reported in the following table 4.2, it is shown a total impact indicator respect to the highest impacting crop. This total indicator, calculated as a mean between FWT%, EU% and HUMT%, would represent a simple and immediate way to include in one indicator the freshwater toxicity, the eutrophication and the human toxicity impact, standardized respect to the highest impacting crop (maize).

In parallel with this, it could be also useful to calculate a comprehensive vulnerability map, to be related with the total impact index. This map would include the vulnerability information to all involved impact indicators. Within GIS framework, a map that contains information coming from more than one map is obtained with the “topological overlay”, through the map calculator tool in the case of the Arcview3.2 software. Maps are superimposed and the information of each location are operated (summed, multiplied, subtracted, divided, etc.) and the resulting map will show for each location (or map pixel) the result of the mathematical operation.

Several approaches may be used to integrate more than one LCA impact indicator with more than one land vulnerability maps. Basically two simple categories may be defined, i.e. with or without an additional operation of synthesis. This operation refers to the calculation of the total impact indicator and the comprehensive vulnerability map. Fresh water toxicity (FWT), eutrophication (EU) and human toxicity (HUMT) were then used as case study in order to define how to integrate them and consequently allocate crops minimizing all their three impacts. The three vulnerability maps were merged testing the following three methods: a) simple additive method (**SAM**) and b) additive method of classified maps (**AMCM**), these last providing the additional synthetic calculations; c) composed multiplicative method (**CMM**), which will not provide the calculation of synthetic indexes and maps.

Simple additive method and crop allocation

In the first method (SAM), all thematic maps used for producing each single vulnerability map to eutrophication (EU), human toxicity (HUMT) and freshwater toxicity (FWT) were overlaid summing for each pixel the vulnerability value assigned to each used environmental characteristic. Therefore, using SAM, all environmental parameters considered inherent to all types of impacts are equally important and they are simply added together giving rise to a map representing the sum of each single score (table 4.1). The procedure is shown schematically in fig. 4.1.

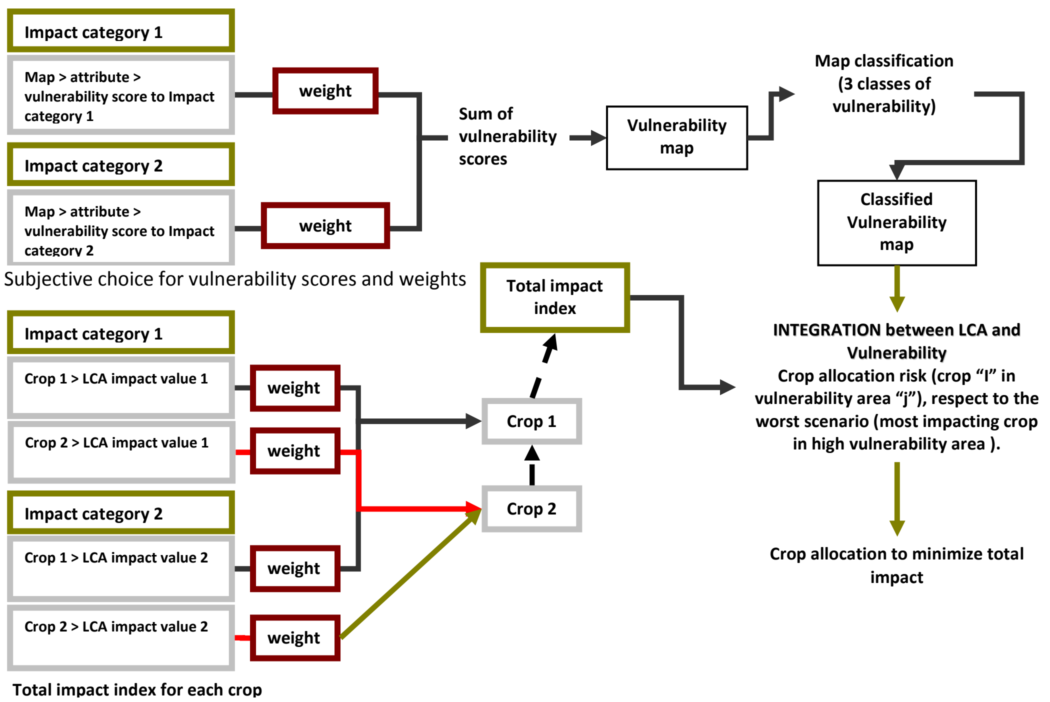


Figure 4.1. Schematic representation of the simple additive method (SAM).

The attribution of the vulnerability score to each land characteristic is in some way still subjective, unless the possibility to use cause/effects relationships between the environmental factor and the impact to the environment. The resulting map will be the resulting sum, for each location (or map pixel), of all impact scores of each considered environmental factor to build all land vulnerability maps.

Of course it is possible to insert weighting factors in order to emphasize one land characteristic respect to another in contributing to the overall vulnerability. This aspect is again a subjective choice. One consideration may be done anyway to support the attribution of weights. For example, in the case of land vulnerability map to human toxicity, only one land characteristic (i.e. population density) is used to define the vulnerability, later or classified in three classes. While, for example, in the case of freshwater toxicity, the vulnerability ranged from 0 to 11 (see fig. 3.3 in chapter 3), and from 0 to 10 (fig. 3.9 in chapter 3) in the case of eutrophication, because of a higher number of involved land characteristics. Human toxicity vulnerability scores may thus be multiplied by a factor >1 in order increase his weight in the case this kind of impact is considered as important for the territory.

Table 4.1. Environmental characteristic used to produce the comprehensive land vulnerability map to FWT, EU and HUMT. Vulnerability score of each layer is summed for each map pixel.

Map layer	Map layer attribute	Vulnerability score
Vulnerability map to FWT		
PTCP_recharge_areas_abcd.shp	Type D	5
PTCP_recharge_areas_abcd.shp	Type A	4
supply_areas.shp	Water supply areas	4
PTCP_zones_derivat_prot.shp	Zones for the derivations protection	3
PTCP_fluvial_tut_areas.shp	Zones for the protection of the riverbeds	3
PTCP_recharge_areas_abcd.shp	Type B	2
PTCP_recharge_areas_abcd.shp	Type C	1
recharge_areas.shp	Recharge areas	1
reserve_areas.shp	Reserve areas	1
Vulnerability map to EU		
Vulnerability map to nitrates	Vulnerable areas	4
Wet areas. Low lands generally flooded during winter or covered by water during all seasons. Riverbeds with vegetation. River valleys and wet areas (from the Land use Map 2003 of the Emilia Romagna Region)	Wet areas	3
Soil map 1:250000 from the Emilia Romagna Region Information service	fine texture	1
	medium texture	3
Vulnerability map to HUMT		
Population density (person km-2)	from 21.71 to 134.87	1
	from 134.87 to 224.53	2
	from 224.53 to 2651.4	3

Fig. 4.2 shows graphically the overlay procedure to obtain the comprehensive vulnerability map following the SAM. HUMT vulnerability scores were increased by 4 in order to reach values comparable with the others vulnerability scores. The map calculator tool of ArcView3.2 was used to sum all map layers.

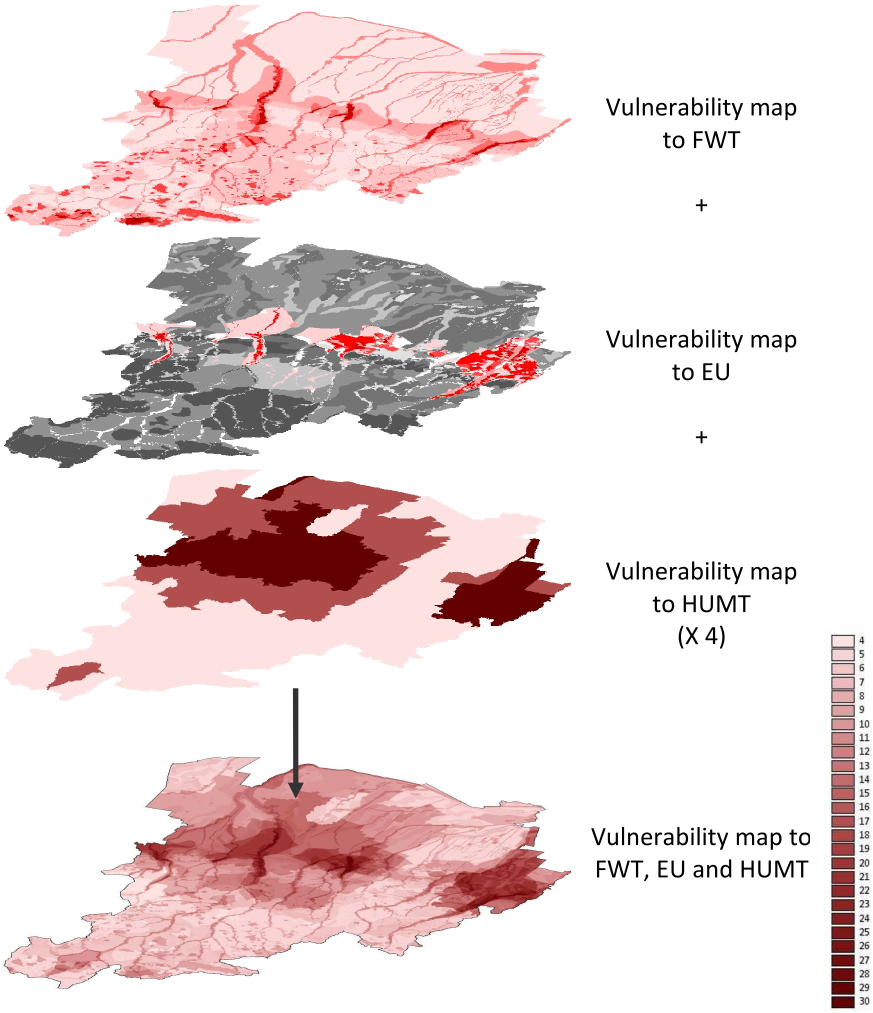


Figure 4.2. Land vulnerability maps overlay based on the simple additive methods (SAM). Each map's pixel represents the vulnerability score deriving from the involved land characteristic used to define vulnerability (table 4.1). Vulnerability score to HUMT were multiplied by 4 as his starting value is lower respect to the other impacts, due to the fact that only one land characteristic (population density) was used to define it.

The resulting total vulnerability map contains vulnerability scores that ranged from 4 to 30 (legend of fig. 4.2).

Ones defined the comprehensive vulnerability map, this last could be classified in three classes and the crop allocation risk may be calculated as already defined when dealing with only one impact indicator, but in this case the impact value to spread among the three allocation risk classes will be the calculated total impact index of each crop (table 3.7 in chapter 3). The extension of the low, moderate and highly vulnerable areas will change on the base of the contemporary vulnerability level of each land factor.

Fig. 4.3 shows the comprehensive vulnerability map to FWT, EU and HUMT, calculated using the SAM, classified in three classes following the equal area classification criteria. High vulnerability areas, still mainly located in the centre of the map, resulted in a higher extension respect to the single vulnerability maps, as well as for moderate lands. This is mainly due to the shape of vulnerable lands to HUMT, which present a high vulnerability corresponding to the Bologna and Imola municipal area, where the extension of highly vulnerable lands of the comprehensive vulnerability map (fig. 4.3) increases.

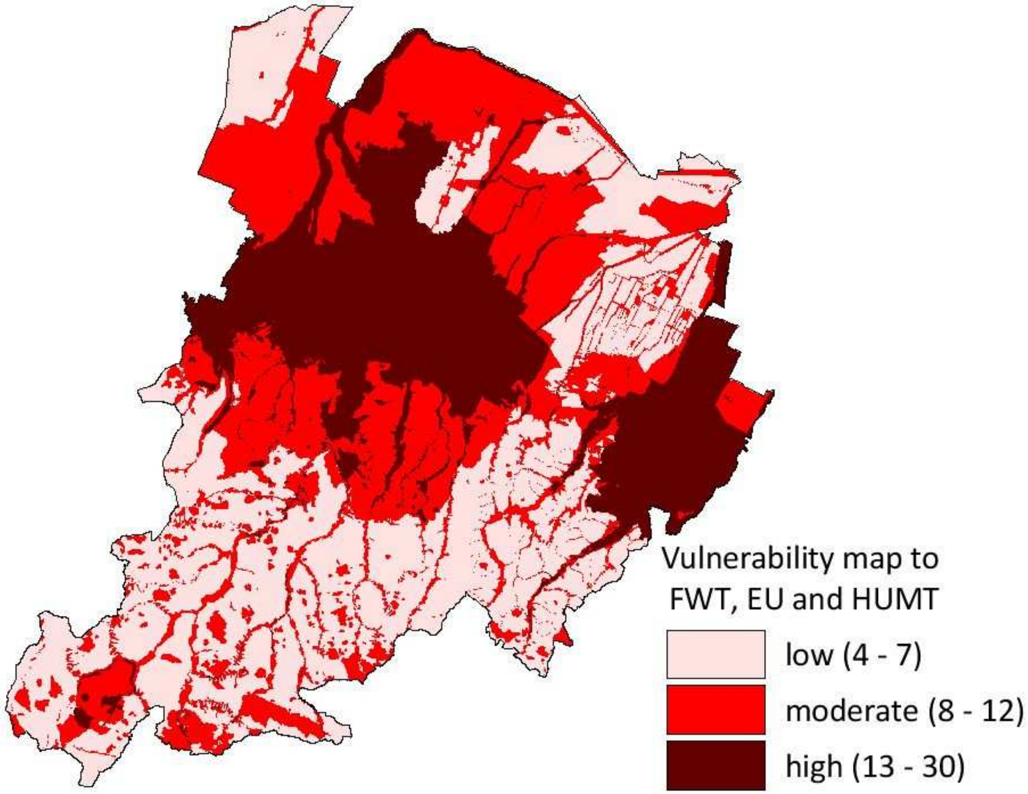


Figure 4.3. SAM – vulnerability map to FWT, EU and HUMT. Vulnerability score are classified in 3 classes of vulnerability (low, moderate and high), based on equal interval method.

Table 4.2. Simple additive method (SAM) vulnerability of municipalities in the province of Bologna.

Municipality	low (%)	moderate (%)	high (%)	Total (ha)
ANZOLA	0.00	0.07	99.93	3619.64
ARGELATO	0.03	0.12	99.85	3511.71
BARICELLA	84.55	15.43	0.01	4555.20
BAZZANO	0.00	0.02	99.98	1383.62
BENTIVOGLIO	81.85	17.94	0.21	5105.77
BOLOGNA	0.00	5.99	94.01	14069.01
BORGO TOSSIGNANO	76.48	10.63	12.89	2905.99
BUDRIO	0.06	91.64	8.30	12033.21
CALDERARA DI RENO	0.00	0.14	99.86	4125.39
CAMUGNANO	58.77	39.27	1.97	9647.47
CASALECCHIO DI RENO	0.00	0.14	99.86	1737.48
CASALFIUMANESE	77.54	17.66	4.80	8198.25
CASTEL D'AIANO	81.38	18.62	0.00	4507.19
CASTEL DEL RIO	75.18	23.43	1.39	5223.21
CASTEL DI CASIO	71.79	27.00	1.20	4729.71
CASTEL GUELFO	0.20	90.20	9.60	2861.29
CASTEL MAGGIORE	0.03	0.00	99.97	3096.71
CASTEL S. PIETRO TERME	48.85	40.78	10.37	14844.33
CASTELLO D'ARGILE	0.00	82.03	17.97	2906.29
CASTELLO DI SERRAVALLE	65.78	27.76	6.45	3907.84
CASTENASO	0.00	0.09	99.91	3575.25
CASTIGLIONE DEI PEPOLI	66.55	32.20	1.25	6563.46
CRESPELLANO	0.00	0.05	99.95	3781.12
CREVALCORE	90.89	9.09	0.02	10227.51
DOZZA	0.05	0.13	99.82	2421.63
FONTANELICE	83.52	11.80	4.68	3650.49
GAGGIO MONTANO	78.98	20.94	0.08	5860.33
GALLIERA	0.00	88.24	11.76	3704.33
GRANAGLIONE	78.58	20.26	1.16	3906.30
GRANAROLO	0.07	0.07	99.86	3438.51
GRIZZANA	78.79	19.97	1.23	7744.68
IMOLA	0.03	0.63	99.34	20434.88
LIZZANO IN BELVEDERE	80.35	19.46	0.20	8530.04
LOIANO	82.20	17.32	0.48	5238.77
MALALBERGO	0.14	85.34	14.53	5377.20
MARZABOTTO	64.31	31.23	4.46	7452.08
MEDICINA	77.92	21.73	0.35	15907.71
MINERBIO	0.08	91.94	7.99	4306.99
MOLINELLA	68.15	31.76	0.08	12756.55
MONGHIDORO	81.19	18.76	0.06	4797.47
MONTE S.PIETRO	0.12	87.89	11.98	7470.78
MONTERENZIO	86.97	12.62	0.41	10532.52
MONTEVEGLIO	0.10	52.66	47.24	3254.04
MONZUNO	74.24	25.21	0.55	6499.62
MORDANO	0.00	83.49	16.51	2128.04
OZZANO	0.09	41.40	58.50	6476.63
PIANORO	0.01	83.07	16.92	10717.80
PIEVE DI CENTO	0.00	0.31	99.69	1578.91
PORRETTA TERME	0.12	73.50	26.38	3392.27
S.AGATA BOLOGNESE	0.03	99.52	0.45	3475.07
S.BENEDETTO VAL DI SAM	70.06	29.67	0.27	6649.74
S.GIORGIO DI PIANO	0.10	0.21	99.69	3043.84
S.GIOVANNI IN PERSICET	0.02	91.73	8.25	11428.36
S.LAZZARO DI SAVENA	0.00	0.13	99.87	4470.66
S.PIETRO IN CASALE	0.03	99.25	0.72	6587.21
SALA BOLOGNESE	0.00	68.34	31.66	4510.64
SASSO MARCONI	0.03	68.24	31.73	9646.06
SAVIGNO	87.65	12.29	0.05	5483.75
VERGATO	76.74	22.65	0.61	5991.96
ZOLA PREDOSA	0.00	1.55	98.45	3774.95
Total	38.58	34.65	26.77	369757.46

Topological overlay of this map with municipality borders of the province gives the possibility to define municipal land portion classified as low, moderate of highly vulnerable. This result is obtained using the union tool of the GeoProcessing Wizarz of Arcview3.2 (table 4.2).

Comparing results of table 4.2 with tables 3.10, 3.13 and 3.15, showing vulnerable land portion to FWT, EU and HUMT respectively, it is clear as the distribution of vulnerable lands among municipalities changes when considering more than one impact indicator. Multiple indicators vulnerability maps increase in general the vulnerability level. 26.77 % of the province was in fact classified as highly vulnerable, while the same in the case of FWT was 1.36 % (table 3.10) and 9.73 % in the case of EU only (table 3.13). 27.10 % was the highly vulnerable land portion when considering only HUMT. Naturally, also the distribution inside each municipality will be different.

As already mentioned, this comprehensive vulnerability map can be used to allocate crop based on a calculated allocation risk value. This allocation value can be defined following the same procedure already illustrated in chapter 3, when dealing with single impact indicator. In this case, the impact value will be the total impact index, i.e. the average impact of the FWT, EU and HUMT percentage respect to maize, the most impacting crop. Results are reported in table 4.3. Values may be distributed among the most impact scenarios, i.e. maize when located in the low, moderate and high vulnerability lands. The resulting map in shown in fig. 4.4.

Table 4.3. Allocation risks for each crop-vulnerable area combination. Total impact index (%) of each crop was used to assign a specific allocation risk value (0-10) to each vulnerability class of the comprehensive vulnerability maps weighted on maize (fig. 4.3). Maize equal to 10 when located in the most vulnerable lands.

Crop	Total impact index %	Vulnerability classes of lands		
		low	moderate	high
maize	**100**	**3.0**	**6.0**	**10.0**
f. sorghum	72.7	2.31	4.36	7.27
rapeseed	65.7	1.97	3.94	6.57
wheat	64.5	1.94	3.87	6.45
sunflower	63.1	1.89	3.79	6.31
cynara	37.1	1.11	2.23	3.71
miscanthus	36.0	1.08	2.16	3.60
giant reed	34.4	1.03	2.06	3.44
switchgrass	25.4	0.76	1.52	2.54

Only switchgrass showed an allocation risk classified as low respect to maize in the whole territory. Integrating 3 impacts, with maize, rapeseed, sunflower, f sorghum and wheat showed the same allocation risk level. Cynara, miscanthus and giant reed showed a moderate allocation risk in highly vulnerable lands (fig.4.4).

Ultimately, once the overall land vulnerability is understood and the different crops characterized in terms of their impacts (FWT, EU and HUMT in our case), one can allocate the more impacting crops in the less vulnerable areas and vice versa, following, as already defined when dealing with only one impact, the indications deriving from fig. 4.4, thus advising for each vulnerability area which crop may be cultivated (fig. 4.5) in order to minimize the FWT, EU and HUMT impacts. In low vulnerable lands, all crops can be cultivated, while in moderate ones cynara, miscanthus and giant reed (and of course switchgrass also) showed a low allocation risk, while in high vulnerability lands only switchgrass showed a low allocation risk.

Compared with optimal allocations considering only one impact indicator, it is still more evident that only switchgrass can be cultivated in high vulnerability lands. In fact, in some cases, e.g. in the case of eutrophication, giant reed and miscanthus were also allowed. In moderate vulnerability area, sunflower and wheat were allowed in the case of FWT, while when considering all impact indicators, they can be cultivated only in low vulnerable areas.

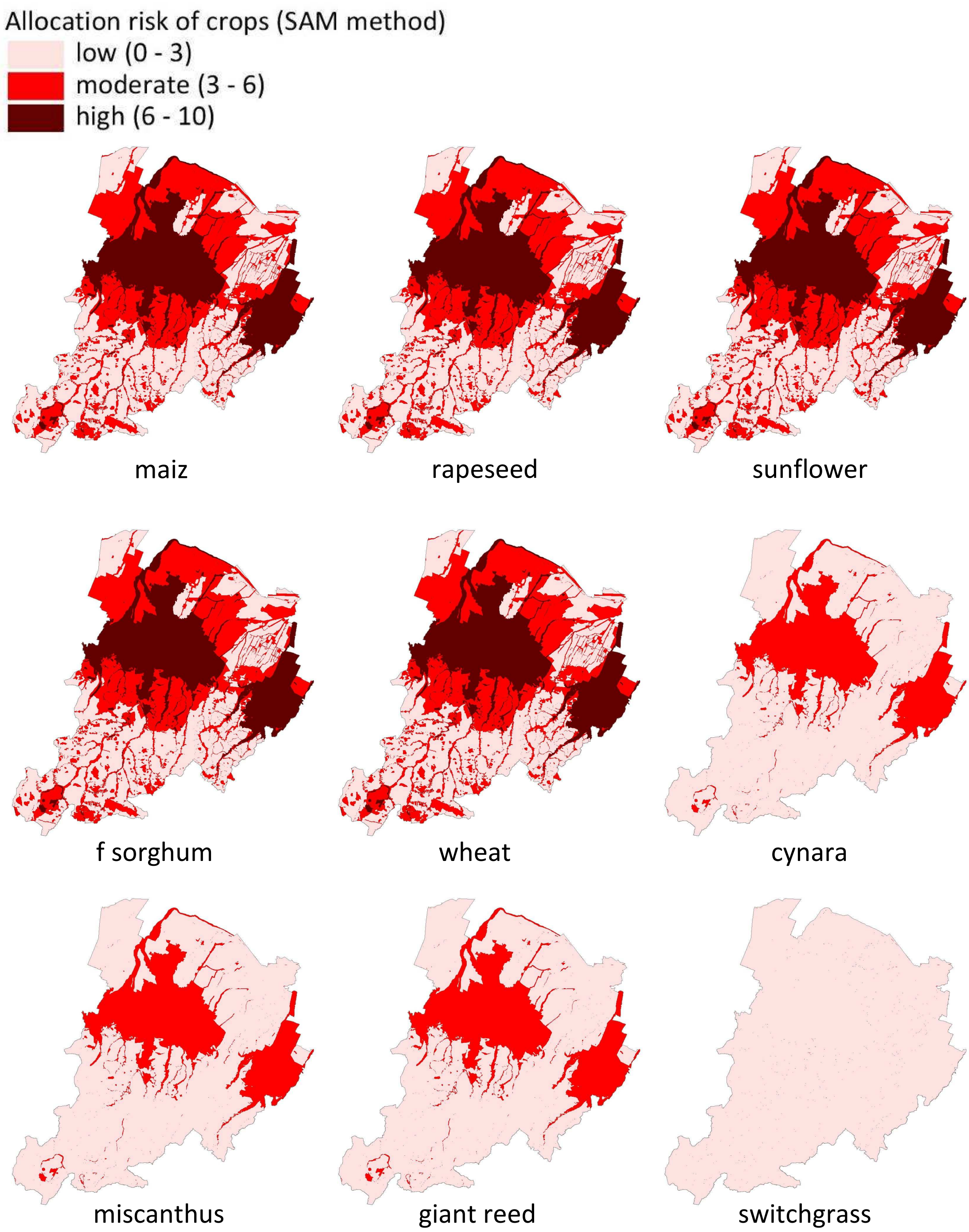


Figure 4.4. Maps of allocation risk of crops based on land vulnerability calculated using SAM as integration method for FWT, EU and HUMT.

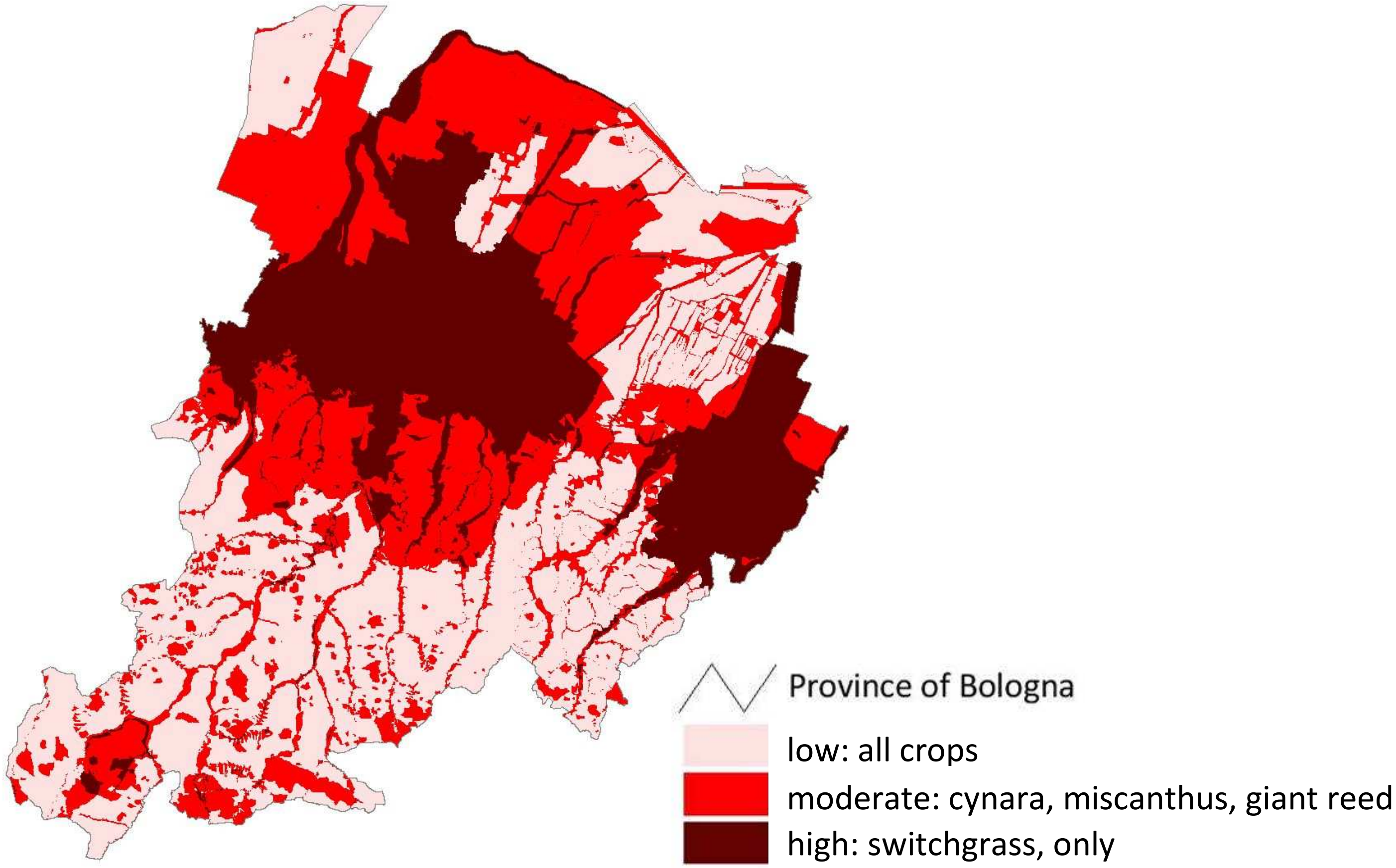


Figure 4.5. Optimal crop allocation to minimize FWT, EU and HUMT risks (SAM integration method). Low, moderate and high vulnerabilities areas are the same as in fig. 4.3.

Additive method of classified maps and crop allocation

In the additive method of classified maps (AMCM), the single vulnerability maps are overlaid after generating maps of constant number of classes, and cumulating the values of each class hereafter. Practically, summing classified maps of vulnerability to EU, FWT and HUMT. The final map will be made up of pixels whose value is this time the sum of each class value (low: 1; moderate: 2; high: 3). Schematically, this approach can be represented in fig. 4.6.

The difference, respect to SAM, is that in this case the relative number of land characteristics used in building single land vulnerability maps are not influencing the final result, because single vulnerability map are firstly all reported at the same number of vulnerability level (low, moderate and high).

After the comprehensive vulnerability map is produced summing values (from 1 to 3) of each single vulnerability map at each location, crop allocation risk can be calculated as for SAM or as when dealing with only one impact indicator, but using the calculated total impact index of table 4.3.

It is worth of notice that when using SAM for integrating vulnerability maps, each environmental characteristics used for all the vulnerability maps are individually considered, thus giving the possibility to introduce a weighting factor to each environmental characteristic if this is recognised as usefull to increase reliability. When cause/effect relationship between environmental factors and vulnerability level, and among different impacts indicators, are known, SAM may be preferred for his flexibility in attributing relative weights.

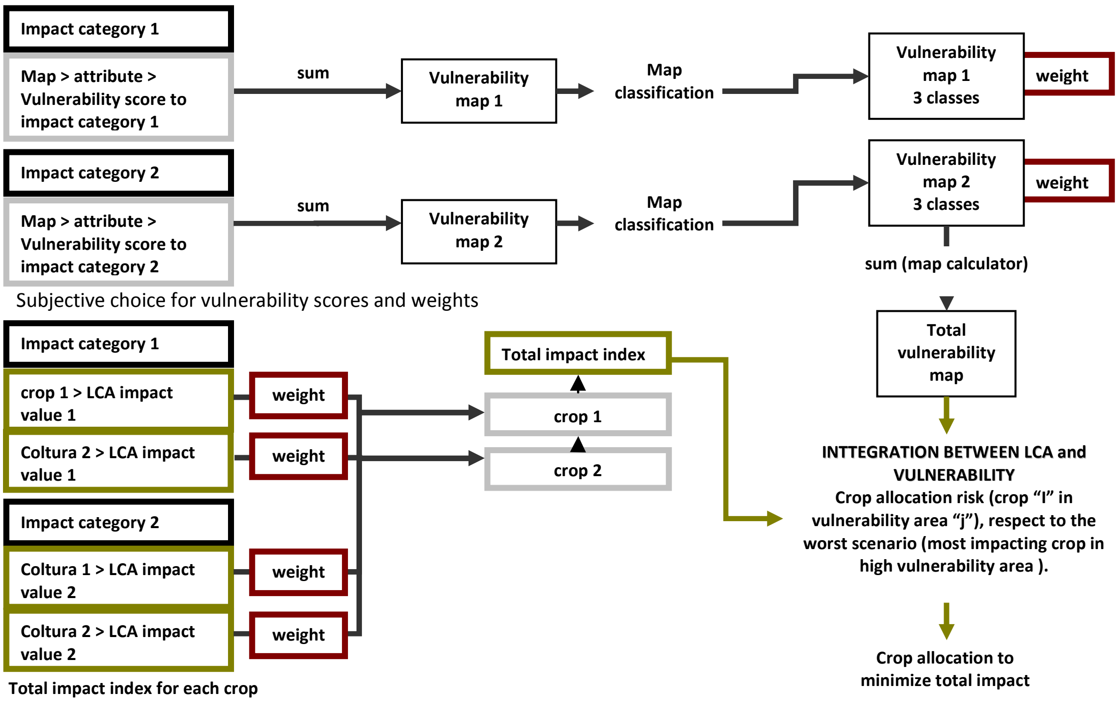


Figure 4.6. Schematic representation of the additive method of classified maps (AMCM).

In the case of undefined relations among LCA impact categories, AMCM should be preferred because attributing the same effect of the different impact indicators to the environment, independently by the involved numbers of environmental factors, because of reporting all individual vulnerability maps to the same effect to the environment (low, moderate and high).

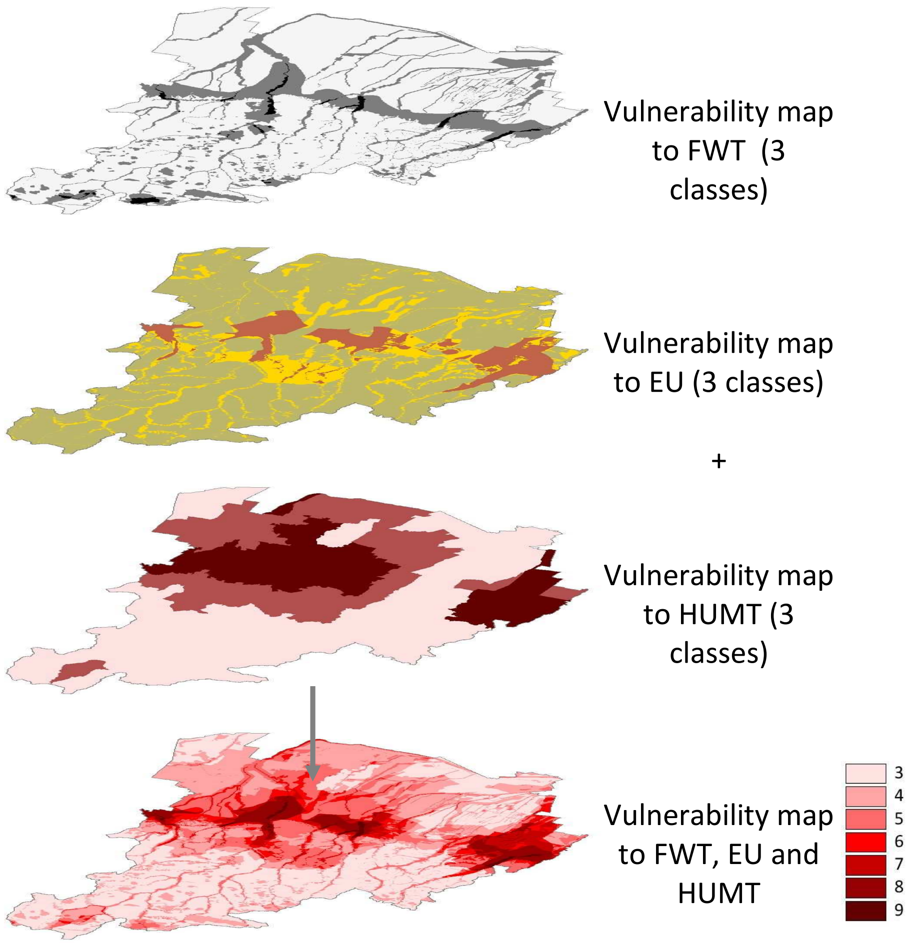


Figure 4.7. Land vulnerability map overlay based on the additive method of classified maps (AMCM). Each map's pixel represent the value of one of the three vulnerability classes (low =1; moderate 2; high = 3) deriving from the classification of single vulnerability map to each impact indicator.

Fig. 4.7 shows the overay process of classified vulnerability maps, carried out using map calculator of ArcView3.2. The resulting map has a vulnerability score that ranged from 3 to 9. Where value is 9 it means obviously that at that location vulnerability was high (3) for each vulnerability map to single impact indicator. Again, this map may be classified in 3 classes of vulnerability following the equal area criteria. The resulting map is showed in fig. 4.8. High vulnerable lands are in the centre of the map, closely to the Bologna and Imola municipality area, the rest of the flat area is prevalently classified as moderate, while higher altitude are prevalently low, with few strings of moderate area mainly corresponding to riverbeds or to other land characteristics linked with the vulnerability to FWT.

Respect to map obtained using SAM, land portions classified as highly vulnerable are smaller, 16.22 % (table 4.4) respect to 26.77 % for SAM (table 4.2). This reduction mainly regards the surroundnig area of the Bologna municipality. Shape and extension of moderate and low vulnerable areas are similar to that obtained using SAM.

Also in this case, overlaying the comprehensive vulnerability map of fig. 4.8 with municipal borders (union tool of ArcView3.2's GeoProcessing Wizard) it is possible to calculate land vulnerable portions for each municipality of the Bologna's province (table 4.4).

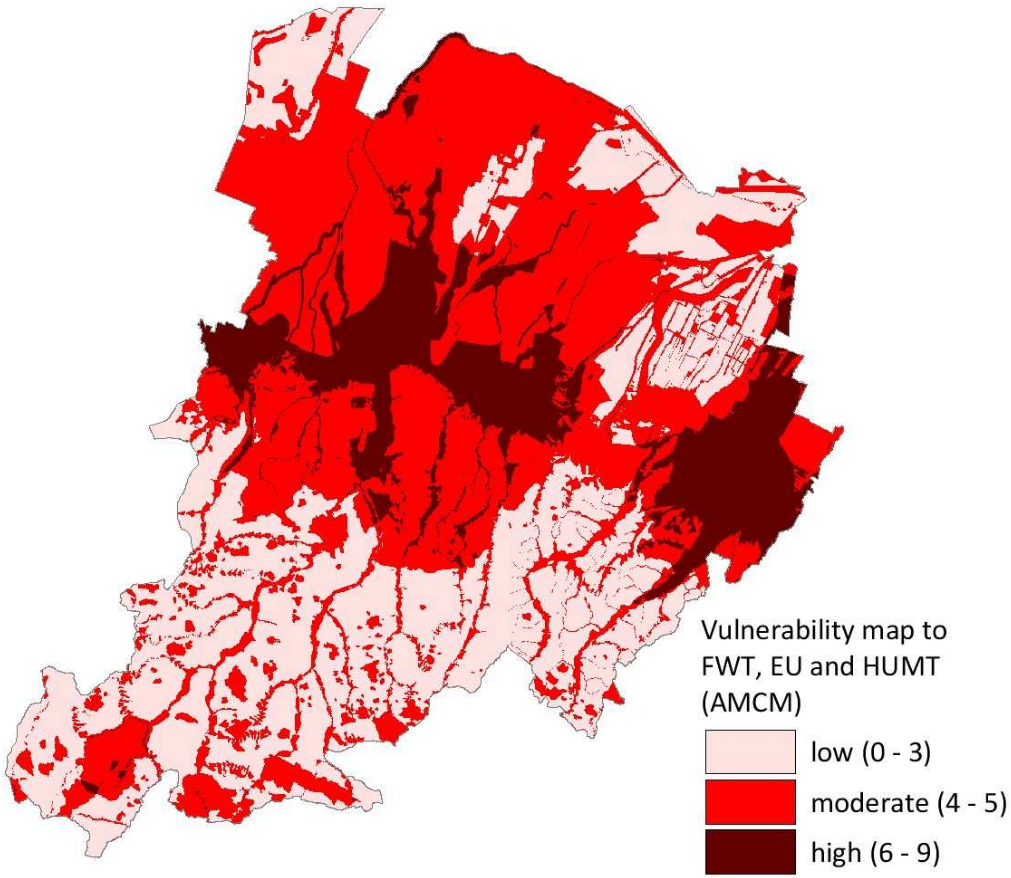


Figure 4.8. AMCM – vulnerability map to FWT, EU and HUMT. Vulnerability score are classified in 3 classes of vulnerability (low, moderate and high), based on equal interval method.

Table 4.4. Additive method of classified map (AMCM) vulnerability of municipalities in the Province of Bologna.

Municipality	low (%)	moderate (%)	high (%)	Total (ha)
ANZOLA	0.00	76.07	23.93	3619.69
ARGELATO	0.02	70.83	29.15	3511.71
BARICELLA	81.40	18.60	0.00	4555.20
BAZZANO	0.00	0.01	99.99	1383.97
BENTIVOGLIO	70.08	29.86	0.06	5105.77
BOLOGNA	0.00	41.82	58.18	14069.00
BORGO TOSSIGNANO	76.35	13.43	10.22	2906.26
BUDRIO	0.05	97.14	2.81	12033.20
CALDERARA DI RENO	0.00	47.35	52.65	4125.39
CAMUGNANO	58.24	41.49	0.26	9647.47
CASALECCHIO DI RENO	0.00	25.38	74.62	1737.48
CASALFIUMANESE	76.96	20.77	2.27	8198.25
CASTEL D'AIANO	79.64	20.36	0.00	4508.11
CASTEL DEL RIO	73.45	26.53	0.03	5223.37
CASTEL DI CASIO	71.03	28.71	0.26	4729.81
CASTEL GUELFO	0.14	92.13	7.73	2861.29
CASTEL MAGGIORE	0.01	32.39	67.60	3096.71
CASTEL S. PIETRO TERME	37.45	57.13	5.42	14844.33
CASTELLO D'ARGILE	0.00	98.14	1.86	2906.29
CASTELLO DI SERRAVALLE	62.91	31.64	5.45	3907.78
CASTENASO	0.00	60.86	39.14	3575.25
CASTIGLIONE DEI PEPOLI	66.42	33.41	0.17	6565.65
CRESPELLANO	0.00	44.68	55.32	3781.22
CREVALCORE	75.63	24.35	0.02	10227.79
DOZZA	0.01	5.70	94.29	2421.63
FONTANELICE	83.60	16.40	0.00	3650.67
GAGGIO MONTANO	78.40	21.57	0.03	5860.33
GALLIERA	0.00	97.29	2.71	3704.33
GRANAGLIONE	77.12	22.47	0.40	3905.97
GRANAROLO	0.03	69.60	30.37	3438.50
GRIZZANA	78.26	21.74	0.00	7744.68
IMOLA	0.04	20.22	79.74	20435.54
LIZZANO IN BELVEDERE	79.72	20.09	0.19	8529.81
LOIANO	78.18	21.37	0.45	5238.77
MALALBERGO	0.10	97.59	2.30	5377.19
MARZABOTTO	64.07	35.24	0.69	7452.08
MEDICINA	66.67	32.99	0.34	15907.70
MINERBIO	0.08	96.55	3.38	4306.99
MOLINELLA	63.61	36.31	0.08	12757.38
MONGHIDORO	81.09	18.89	0.02	4797.77
MONTE S.PIETRO	0.09	90.94	8.97	7470.78
MONTERENZIO	86.57	13.32	0.11	10533.08
MONTEVEGLIO	0.10	65.69	34.21	3254.11
MONZUNO	73.47	26.19	0.35	6499.62
MORDANO	0.00	93.08	6.92	2128.08
OZZANO	0.07	55.08	44.85	6476.63
PIANORO	0.01	86.19	13.80	10717.80
PIEVE DI CENTO	0.00	48.63	51.37	1579.14
PORRETTA TERME	0.09	88.54	11.37	3392.27
S.AGATA BOLOGNESE	0.02	99.74	0.24	3475.59
S.BENEDETTO VAL DI SAM	66.07	33.87	0.06	6649.99
S.GIORGIO DI PIANO	0.10	94.44	5.46	3043.84
S.GIOVANNI IN PERSICET	0.01	98.83	1.16	11428.34
S.LAZZARO DI SAVENA	0.00	15.41	84.59	4470.65
S.PIETRO IN CASALE	0.03	99.88	0.09	6587.21
SALA BOLOGNESE	0.00	95.94	4.06	4510.64
SASSO MARCONI	0.03	71.38	28.59	9646.06
SAVIGNO	81.97	17.98	0.05	5483.44
VERGATO	75.50	24.48	0.01	5992.04
ZOLA PREDOSA	0.00	32.79	67.21	3774.95
Total	36.43	47.35	16.22	369764.59

Obviously, in some municipalities the distribution of vulnerable lands will be different between the to integration methods (SAM and AMCM). In particular in the case of the municipality of Anzola and Argelato, highly vulnerable lands are around 99 % in the case of SAM (table 4.2) and around 24% and 29 % in the case of AMCM (table 4.4). In general, also comparing the comprehensive vulnerability map with the single ones, SAM seems to overestimate higly vulnerable lands.

Ones obtained the vulnerability map calculated integrating all impact indicators, crops can be distributed based to their allocation risk, that still may be calculated as already mentioned in the case of the SAM description. Also for AMCM the total impact index is used to define allocation risk, thus resulting values will be the same already reported in table 4.2. Consequently, also their rappresentation on a map will bring to similar conclusion about the crop that should be grown in all vulnerable lands. Only the extension of vulnerable land portions respect to the ones defined with the AMCM will be different. Fig. 4.9 reports the map of the optimal crop allocation in order to minimize the allocation risk for FWT, EU and HUMT, on the base of the comprehensive vulnerability map defined using AMCM. Again, considering 3 impact indicators, only switchgrass presented generally a low environmental risk respect to maize.

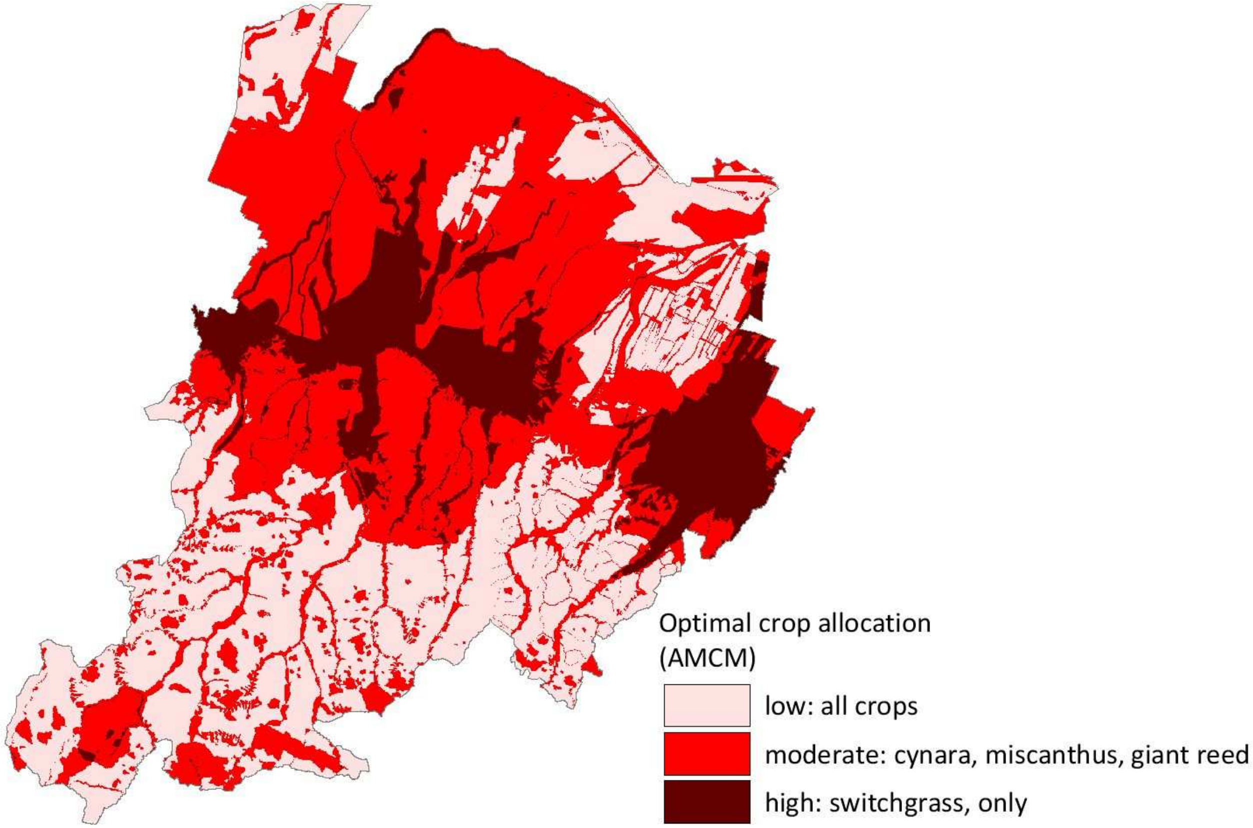


Figure 4.9. Optimal crop allocation to minimize FWT, EU and HUMT risks (AMCM integration method). Low, moderate and high vulnerabilities areas are the same as in fig. 4.8.

In general, apart of all pedo-climatic constraints that may define the crop allocation and with which the bi-directional approach can be coupled (Di Virgilio, Fazio et al. 2010), with respect to the first step of this study which included only one impact indicator, merging fresh water toxicity, eutrophication and human toxicity into a single map resulted in a significant different allocation of energy crops. Rapeseed, wheat, sunflower and f sorghum showed similar environmental risks, while only switchgrass showed the lowest environmental risks. Maize confirmed the highest contamination risks thus to suggest a land allocation of this crop in the lowest vulnerability lands. When merging impacts, miscanthus and giant reed resulted in a higher allocation risk respect to using only eutrophication.

When allocating crops basing on the environmental impact of their production chain, the most natural implementation of this method will be the definition of a unique total impact index representing all impacts with a local effect to be used in the SAM and AMCM integration methods. This operation introduce a lack of information due to the avegare operation. The following procedure, the composed multiplicative method (CMM), will calculate allocation risk of each crop without the need of a total impact index and of a comprehensive vulnerability map.

Composed multiplicative method and crop allocation

Previously illustrated integration methods, the “simple additive method (SAM)” and the “additive method of classified maps (AMCM)”, provide the use of an additional operation to synthesize impact indexes and land vulnerabilities. The production of a total impact index and of a comprehensive vulnerability map introduces uncertainty in giving weighting factors or when classifying vulnerability score in the 3 vulnerability classes. Moreover, this aspect is more evident if the number of environemtal indicators increases.

The composed multiplicative method (CMM) uses vulnerability maps to single impact indicator and gives the possibility to allocate crops considering multiple indicators without building a comprehensive vulnerability map and then without classify the vulnerability values, and also without defining a total impact index. With this method the single vulnerability maps defined for each impact indicator are overlayed throught weighting factor that are the values of the impact indicators. The values associated with the vulnerability of an individual vulnerability map are multiplied by the environmental impact score of each crop with respect to that environmental parameter, and for each map pixel. Schematically, the procedure is represented in fig. 4.10.

In order to be overlayed, again vulnerability maps should be in a raster format and with the same pixel resolution. The map calculator tool of Arcview3.2 ESRI is used to make operation. With this approach each crop will have its map showing its allocation risk levels. This mean that for each location, it is possible to know wich crop has the lower allocation risk value and to suggest it for that location.

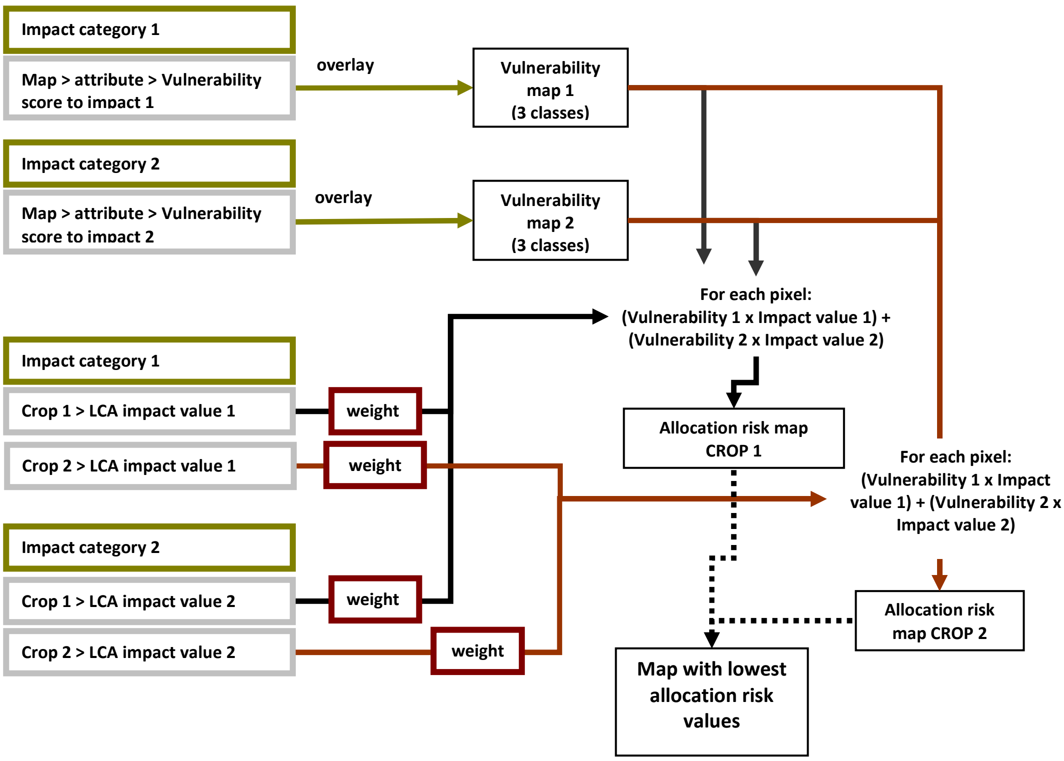


Figure 4.10. Schematic representation of the simple multiplicative method (SMM).

More in detail, crop may be distributed basing to a calculated crop impact allocation risk score when crop is located in a given vulnerable area, which the principle is the same when dealing with only one impact indicator, but in this case, for each pixel and for each crop, the allocation risk is calculated as:

(LCA impact index 1 X its vulnerability score on the map 1)

+

(LCA impact 2 X its vulnerability score on the map 2).

E.g. in the case of rapeseed the allocation risk map is calculated, each map pixel, as follow:

[82.9 (that is the EU% in table 3.7) X Vulnerability score in the vulnerability map to EU (fig. 3.10)]
+
[63.5 (that is the HUMT% in table 3.7) X Vulnerability score in the vulnerability map to HUMT (fig. 3.13)]
+
[(50.8 (that is the FWT% in table 3.7) X Vulnerability score in the vulnerability map to FWT (fig. 3.4)]

For each pixel the crop with the lowest value will represent the lowest impacting option.

Vulnerability maps that can be used in this method are the ones reporting the vulnerable score as calculated after overlaying all used land characteristics, or after their classification in three classes of vulnerability. The uses of vulnerability scores of course would be the best option for this method, because the classification operation is completely avoided. This could be possible if a standard procedure for obatining land vulnerability maps are available and only if the different impact indicators may be in someway mutually comparable. A procedure that could be usefull for this purpose it could be something inspired to the standardization step occurring in the LCA procedure, which is described in chapter 2. A simple and fast way to make vulnerability maps comparable is to use the classified vulnerability maps, where the territory is divided in the same number of classes (e.g. low, moderate and high vulnerability level). In this way also a simpler and more immediate interpretation of the vulnerability maps is possible. The vulnerability value to be used in the

CMM may simply be 1, 2 and 3 for the low, moderate and high classes, respectively.

Again, as regards for impact indicators, the use of the percentage respect to maize (the most impacting crop), make indicators all comparable. Resulting allocation risk maps of each crop will be respect to the worst allocation scenario (maize when located in the high vulnerable area).

CMM gives the possibility to show relative levels of impact of each crop for a given area. As a total vulnerability map was not calculated, each crop may present vulnerable areas that differ in shape and extension.

Already defined impact indicators FWT, EU, and HUMT, were thus used to apply the CMM method. Used numerical impact values of all food and no-food production chains considered in the case study are the % impact respect to maize (the most impacting crop), shown in table 3.7, following again reported (table 4.5) for a easier reading.

Table 4.5. Eutrophication value (EU, expressed as kg ha^{-1} of equivalent phophate ions (PO_4^{-3} eq.), human toxicity (HUMT) and toxicity to freshwaters (FWT), these two last expressed as kg ha^{-1} of 1,4-diclorobenzene eq. (1,4-DC eq.), and as % respect to the highest impacting crop (maize). The total impact index is calculated as average of the % values of impacts: [EU%) + (HT%) + (FWT%)] / 3.

Crop	FWT 1,4-DC eq. (kg ha^{-1})	%	EU PO_4^{3-} eq. (kg ha^{-1})	%	HUMT 1,4-DC eq. (kg ha^{-1})	%	Total impact index %
maize	**199**	**100**	**5.56**	**100**	**1810**	**100**	**100**
f sorghum	128.0	**64.3**	4.38	**78.8**	1360	**75.1**	**72.7**
rapeseed	101.0	**50.8**	4.61	**82.9**	1150	**63.5**	**65.7**
wheat	99.1	**49.8**	4.37	**78.6**	1180	**65.2**	**64.5**
sunflower	90.5	**45.5**	4.46	**80.2**	1150	**63.5**	**63.1**
cynara	74.3	**37.3**	1.85	**33.3**	738	**40.8**	**37.1**
miscanthus	76.9	**38.6**	1.67	**30.0**	709	**39.2**	**36.0**
giant reed	73.9	**37.1**	1.64	**29.5**	661	**36.5**	**34.4**
switchgrass	50.3	**25.3**	1.37	**24.6**	474	**26.2**	**25.4**

The allocation risk for each crop and for each map pixel is calculated using the map tool calculator of ArcView3.2. Inserted equations are here reported. The term between square branches indicates the vulnerability value (1, 2 or 3) at each map pixel.

[Allocation risk of crop 1 = (EU vulnerability X EU % impact respect to maize) + (HUMT vulnerability X HUMT% impact respect to maize) + (FWT vulnerability X FWT% impact respect to maize)]

- maize: ([Vuln_EU] * 100) + ([Vuln_HUMT] * 100)+ ([Vuln_FWT] * 100)
- cynara: ([Vuln_EU] * 33.3) + ([Vuln_HUMT] * 40.8)+ ([Vuln_FWT] * 37.3)
- rapeseed: ([Vuln_EU] * 82.9) + ([Vuln_HUMT] * 63.5)+ ([Vuln_FWT] * 50.8)
- wheat: ([Vuln_EU] * 78.6) + ([Vuln_HUMT] * 65.2)+ ([Vuln_FWT] * 49.8)
- sunflower: ([Vuln_EU] * 80.2) + ([Vuln_HUMT] * 63.5)+ ([Vuln_FWT] * 45.5)
- miscanthus: ([Vuln_EU] * 30) + ([Vuln_HUMT] * 39.2)+ ([Vuln_FWT] * 38.6)
- switchgrass: ([Vuln_EU] * 24.6) + ([Vuln_HUMT] * 26.2)+ ([Vuln_FWT] * 25.3)
- f sorghum: ([Vuln_EU] * 78.8) + ([Vuln_HUMT] * 75.1)+ ([Vuln_FWT] * 64.3)
- giant reed : ([Vuln_EU] * 29.5) + ([Vuln_HUMT] * 36.5)+ ([Vuln_FWT] * 37.1)

Table 4.6 shows the resulting variation range of values calculated according to above equations. Maize shows the higher variation range.

Table 4.6. Allocation risk range of variation of crops in the province of Bologna.

Crop	min	max	variation
maize	**300**	**900**	**600.0**
f sorghum	218.2	654.6	436.4
rapeseed	197.2	591.6	394.4
wheat	193.6	580.8	387.2
sunflower	189.2	567.6	378.4
cynara	111.4	334.2	222.8
miscanthus	107.8	323.4	215.6
giant reed	103.1	309.3	206.2
switchgrass	76.1	228.3	152.2

It also represents the maximum allocation risk that may be found in the territory. This value does not directly quantify a phenomena, but it is useful for defining the allocation risk classes of the other crops (fig. 4.12). The max and min values were used for the definition of a unique scale of representation in order to use the same legend for all crops (fig. 4.11), at the end indicating the level of their impact compared to maize. Values represent the allocation risk with respect to maize of a crop in a certain portion of land which has a vulnerability classified as low, medium or high according to the vulnerability map of the three considered factors (HUMT, FWT and EU).

Taking into account 3 impacts (eutrophication, human toxicity and freshwater toxicity), sorghum, rapeseed and wheat showed higher allocation risk values after maize, which remains the most impacting crop. Among annual crops, sunflower showed in general an overall lower impact. Cynara, miscanthus and giant reed showed much lower impact respect to annual crops, while switchgrass was found to have the lowest allocation risk respect to maize, represented by a general lower grey intensity of his allocation risk map (fig. 4.11).

For a more useful and immediate visualization, also in this case the allocation risk can be classified in three classes, maps are shown in fig. 4.12.

After the classification, maize presented an high allocation risk in the central part of the Province (fig. 4.12), corresponding mainly to areas classified as vulnerable to nitrate by the Water Protection Plan and also as the most densely populated. F sorghum showed a risk classified as high in only a few strips, where the vulnerability to eutrophication is high and where are located main areas for the protection of groundwaters and aquifers. Rapeseed, wheat and sunflower showed an impact classified as medium in the central area of the territory, while switchgrass did not show significant impacts throughout the province, respect to maize and other crops. Even cynara, miscanthus and giant reed showed a low impact, except for the most vulnerable areas from the point of view of the protection of water, where these three crops showed an impact classified as medium.

The elaboration of these maps within ArView3.2 gives the possibility to calculate land hectares and portions, reported in table 4.7.

16.24 % (60083 ha) of the province showed an allocation risk classified as high if maize will be allocated, and 0.58 % (2128 ha) in the case of f sorghum.

The other crops resulted in an allocation risk classified as moderate and low. All perennial crops may be prevalently considered with a low allocation risk in the whole province.

Table 4.7. Extension (ha) and % on the total province extension of lands where crops showed allocation risks classified as low, moderate and high respect to maize.

	low (ha)	%	moderate (ha)	%	high (ha)	%
maize	134493	36.36	175306	47.40	60083	16.24
f sorghum	238678	64.53	129075	34.90	2128	0.58
rapeseed	239813	64.84	130068	35.16	0	0.00
wheat	239813	64.84	130068	35.16	0	0.00
sunflower	249282	67.40	120599	32.60	0	0.00
cynara	367554	99.37	2327	0.63	0	0.00
giant reed	367753	99.42	2128	0.58	0	0.00
miscanthus	367753	99.42	2128	0.58	0	0.00
switchgrass	369881	100.00	0	0.00	0	0.00

Ones defined for a production district all pedoclimatic constraints, that means integrating the presented approach with land suitability studies (Di Virgilio, Fazio et al. 2010) and a sustainable food-no food crop balance, for each location the crop with the lowest value will ensure the best option under the environmental point of view, that in general is represented by perennial crops. This aspect deals with the integration of the LCS-GIS approach with the current land use and with land suitability studies based on pedo-climatic factors. Possibilities coming from these interaction are illustrated in the following chapter 6 “Prospect on applications”.

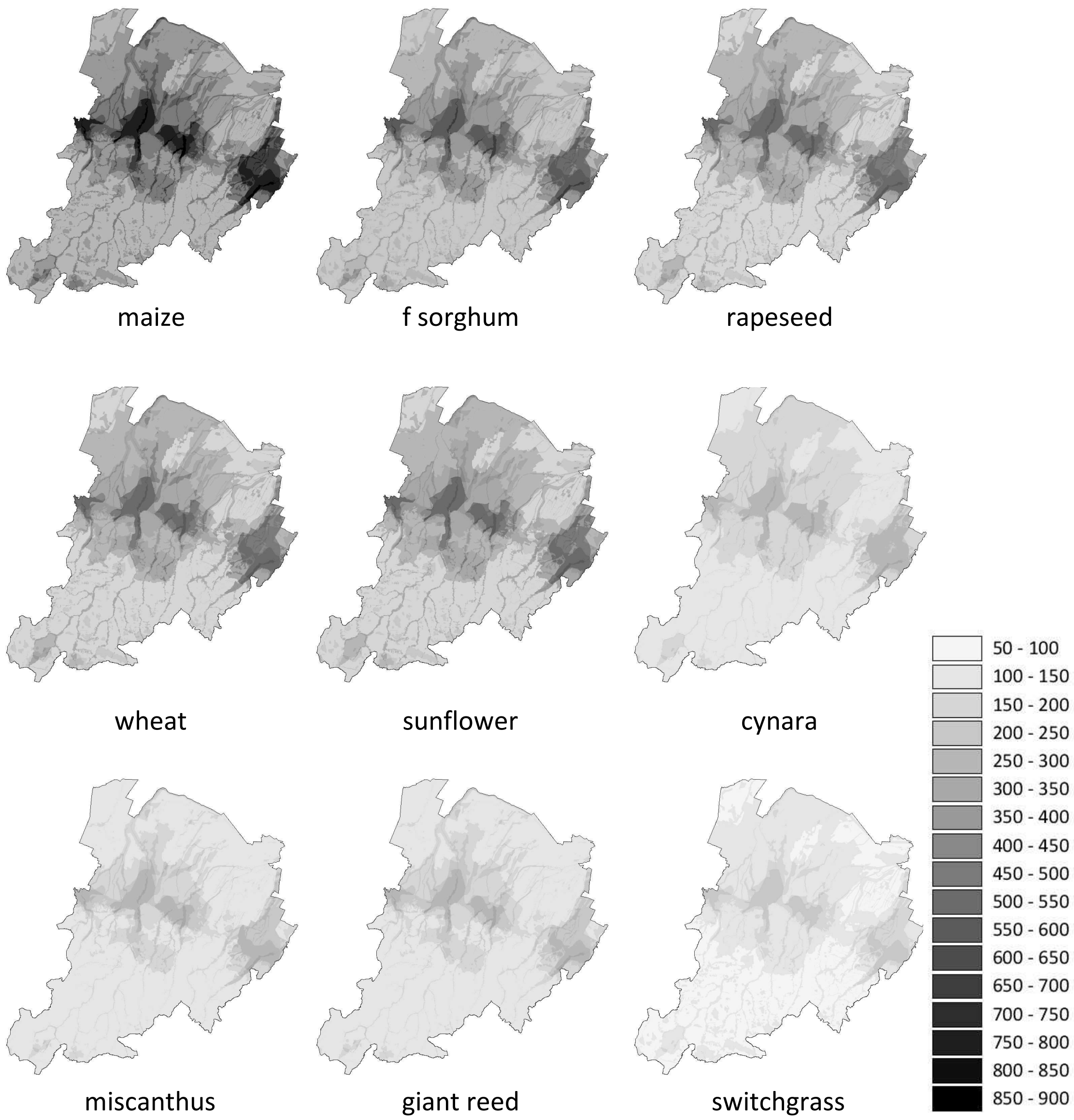


Figure 4.11. Allocation risk considering FWT, HUMT and EU of crops in the province of Bologna, represented with the same gray scale. Darker colours indicate higher allocation risk.

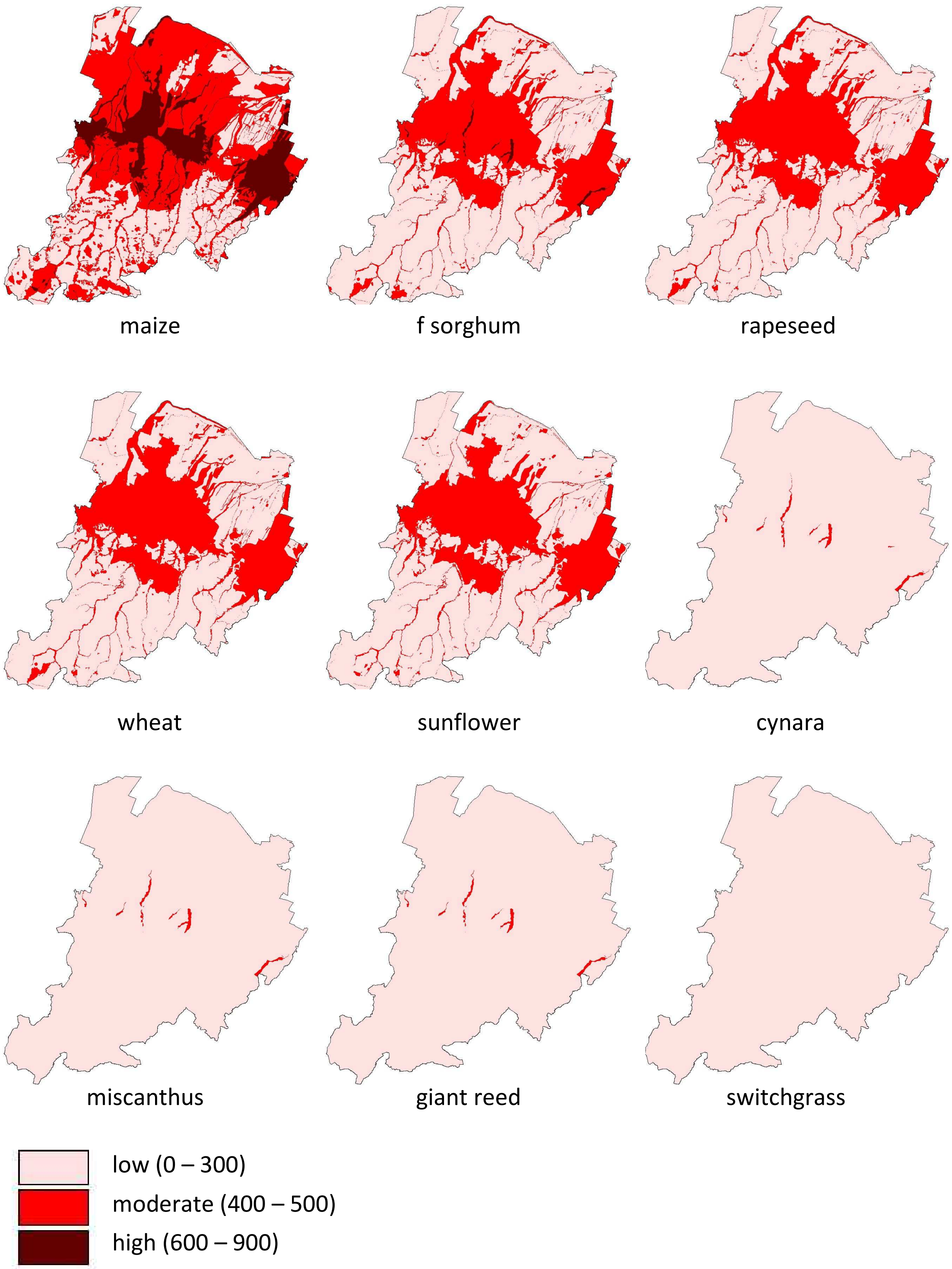


Figure 4.12. Allocation risk for each crop respect to maize in the Province of Bologna. Classification of maps in three classes (low, moderate and high).

The CMM well suits the possibility to use more than two impact categories. Of course considering all impact indicators appraisable with LCA among all existing impact assessment methods, only impacts with local effect can be taken into account, and omitting all impacts with global effect as global warming potential, because of the impossibility to relate their negative effects on the environment with site-specific land characteristics.

With the CMM it is not possible to have a single map that summarizes the optimal land allocation, as the one for example of fig. 4.9, because the legend of fig. 4.11 (or of fig. 4.12 if classified) represents the allocation risk for each map pixel, and not the allocation risk each vulnerable land portion. For each crop that portion will be different because considered vulnerable area are differents each land vulnerability map, in other words all crops are not related to the same single comprehensive vulnerability map, but to 3 ones with different vulnerable land extensions.

Maps of fig. 4.11 and 4.12 thus gives the indication of showing for each map pixel wich crop has the lowest allocation risk. Switchgrass is the crop that ensure the lowest allocation risk in all the territory, but of course other constraints could act in preferring other crops: e.g. food – no food competition, agronomic limitations linked to the mechanization, social constraints as the difficulty on accepting a novel and perennial crop, etc.

Topological overlay of allocation risk map (fig. 4.12) with the map of municipal borders, using the union tool of the ArcView3.2'S

GeoProcessing Wizard, gives the possibility to calculate allocation risk presence for each municipality of the province. Using the allocation risk map of maize (fig. 4.12) representing also in the case of CMM the worst allocation scenarios, results are shown in table 4.8. In the case of maize, values are the same as reported in table 4.4, where vulnerable land portions derive from the use of the AMCM. This may be repeated for each crop. The CMM, thus also gives the possibility to each municipality governmental board, to have the information of the vulnerable land portions for each crop and consequently taking planning decisions on land use.

Table 4.8. Composed multiplicative method (CMM) vulnerability of municipalities in the Province of Bologna. Data refers to maize allocation risk map overlaid with municipal borders.

Municipality	low (%)	moderate (%)	high (%)	Total (ha)
ANZOLA	0.00	76.07	23.93	3619.69
ARGELATO	0.02	70.83	29.15	3511.71
BARICELLA	81.40	18.60	0.00	4555.20
BAZZANO	0.00	0.01	99.99	1383.97
BENTIVOGLIO	70.08	29.86	0.06	5105.77
BOLOGNA	0.00	41.82	58.18	14069.00
BORGO TOSSIGNANO	76.35	13.43	10.22	2906.26
BUDRIO	0.05	97.14	2.81	12033.20
CALDERARA DI RENO	0.00	47.35	52.65	4125.39
CAMUGNANO	58.24	41.49	0.26	9647.47
CASALECCHIO DI RENO	0.00	25.38	74.62	1737.48
CASALFIUMANESE	76.96	20.77	2.27	8198.25
CASTEL D'AIANO	79.64	20.36	0.00	4508.11
CASTEL DEL RIO	73.45	26.53	0.03	5223.37
CASTEL DI CASIO	71.03	28.71	0.26	4729.81
CASTEL GUELFO	0.14	92.13	7.73	2861.29
CASTEL MAGGIORE	0.01	32.39	67.60	3096.71
CASTEL S. PIETRO TERME	37.45	57.13	5.42	14844.33
CASTELLO D'ARGILE	0.00	98.14	1.86	2906.29
CASTELLO DI SERRAVALLE	62.91	31.64	5.45	3907.78
CASTENASO	0.00	60.86	39.14	3575.25
CASTIGLIONE DEI PEPOLI	66.42	33.41	0.17	6565.65
CRESPELLANO	0.00	44.68	55.32	3781.22
CREVALCORE	75.63	24.35	0.02	10227.79
DOZZA	0.01	5.70	94.29	2421.63
FONTANELICE	83.60	16.40	0.00	3650.67
GAGGIO MONTANO	78.40	21.57	0.03	5860.33
GALLIERA	0.00	97.29	2.71	3704.33
GRANAGLIONE	77.12	22.47	0.40	3905.97
GRANAROLO	0.03	69.60	30.37	3438.50
GRIZZANA	78.26	21.74	0.00	7744.68
IMOLA	0.04	20.22	79.74	20435.54
LIZZANO IN BELVEDERE	79.72	20.09	0.19	8529.81
LOIANO	78.18	21.37	0.45	5238.77
MALALBERGO	0.10	97.59	2.30	5377.19
MARZABOTTO	64.07	35.24	0.69	7452.08
MEDICINA	66.67	32.99	0.34	15907.70
MINERBIO	0.08	96.55	3.38	4306.99
MOLINELLA	63.61	36.31	0.08	12757.38
MONGHIDORO	81.09	18.89	0.02	4797.77
MONTE S.PIETRO	0.09	90.94	8.97	7470.78
MONTERENZIO	86.57	13.32	0.11	10533.08
MONTEVEGLIO	0.10	65.69	34.21	3254.11
MONZUNO	73.47	26.19	0.35	6499.62
MORDANO	0.00	93.08	6.92	2128.08
OZZANO	0.07	55.08	44.85	6476.63
PIANORO	0.01	86.19	13.80	10717.80
PIEVE DI CENTO	0.00	48.63	51.37	1579.14
PORRETTA TERME	0.09	88.54	11.37	3392.27
S.AGATA BOLOGNESE	0.02	99.74	0.24	3475.59
S.BENEDETTO VAL DI SAM	66.07	33.87	0.06	6649.99
S.GIORGIO DI PIANO	0.10	94.44	5.46	3043.84
S.GIOVANNI IN PERSICET	0.01	98.83	1.16	11428.34
S.LAZZARO DI SAVENA	0.00	15.41	84.59	4470.65
S.PIETRO IN CASALE	0.03	99.88	0.09	6587.21
SALA BOLOGNESE	0.00	95.94	4.06	4510.64
SASSO MARCONI	0.03	71.38	28.59	9646.06
SAVIGNO	81.97	17.98	0.05	5483.44
VERGATO	75.50	24.48	0.01	5992.04
ZOLA PREDOSA	0.00	32.79	67.21	3774.95
Total	36.43	47.35	16.22	369764.59

5. General discussion

Main aspects related to the defined LCA-GIS approach

Classification issue

Subjectivity of choices

Main conclusions from the method use

Highlights

The characterization factor is the first step within LCA procedure where it may be possible to act in order to “adjust” the impact to the site-specific vulnerability. The proposed LCA-GIS approach postpones it at the end of the LCA procedure, through the calculation of crop-land allocation risks, thus avoiding to modify LCA database and software. The environmental impact of perennials was recognized as quite low, thus giving the possibility to introduce a new low impacting land use in order to maximixe the environmental sustainability. Classification it is used at several levels at it represents an important determinant that can also modify results. The classification criteria must be chosen carefully based on specific goals and circumstances. Maximum transparency it must be maintained, justifying as much as possible choices in order to ensure full traceability of the results. The definition of a standard methodology to provide consistent vulnerability maps and for their integration is required.

Main aspects related to the defined LCA-GIS approach

The link between LCA impact values and the site specificity of the territory is the key aspect in the proposed approach. In the LCA, the impact indicator value, e.g. eutrophication, is calculated after the inventory of all emitted substances related to that kind of impact. After that, these substances are multiplied by a characterization factor, that quantifies the contribution of each substance to the impact indicator (Brentrup, Kusters et al. 2004). All production chains act on the territory, and the spatialization of the LCA impact indicators is very important, in particular for that production chains that are strictly depending to local environment condition, e.g. agricultural crop chains. The spatialization of impact indicator gives the possibility to weight the impact to local specific condition. The characterization factor is the first step within LCA procedure where it may be possible to act in order to “adjust” the impact level to the site-specific conditions. Thus for each substance of the inventory and based on the land vulnerability map, the characterization factor may be geographically referred to the land vulnerability, where this vulnerability is high, characterization factor can be increased. Fundamentally it could be compared to the normalization step occurring in the LCA procedure (Brentrup, Kusters et al. 2004), standardizing impact indicators to the location. Impact indicators will be no more a single value for each crop, but a range of value showed in a map, thus defining a geo-LCA tool. Moreover, within all substances and characterization factors that contribute to the impact indicator, only the ones with recognized local effect can be chosen, increasing reliability of the method. This procedure, although desirable, requires deep knowledge on impact definitions and about the inner running operations of the LCA software. The here proposed approach postpones the integration with land site-specific characteristics at the end of the LCA procedure, through the calculation of different crop-land allocation risks using impact values of commercially ready to use LCA databases and procedures, thus represent a simple and fast tool. Further more, potentially, all impact indicators available in the bibliography may be used, without acting on the procedure, thus giving the possibility to use the academic recourses to easily have impact indicator for a huge number of crop or agro-production chains.

The LCA-GIS method well fits the situation in which several crops may be used to satisfy the same function, as dedicated crops are for energy production. The environmental impact of perennials is recognized quite low respect to annual crops and some food crops, together their high level of adaptability to several pedo-climatic conditions. The crop-to-environment allocation approach gives thus the possibility to introduce a new low impacting land use and to reorganize the distribution of food and no-food crops in order to minimize the impact for the environment.

When allocating crops basing on the multiple environmental impact of their production chain, the most natural implementation of this method will be the definition of a unique total impact index representing all impacts with a local effect to be used in the SAM and AMCM integration methods. The simplest way to calculate it is to make average of considered impacts. The average operation brings to a loss of information, thus the CMM has to be preferred because it gives the possibility to consider all single impacts.

The LCA-GIS approach can be considered as a factor to be added to pedo-climatic analysis of the environment when dealing with land suitability studies. This helps in bringing multicriteriale approaches also increasing as many as possible the number of impact indicators with local effects, that are, as already mentioned, only impacts for which it is possible to define an area of interaction or a mutual effect with some land factors. This means that only few impact categories can be used in the LCA-GIS approach. Anyway the multi-criteria approach should be as wide as possible. Also incorporating of all possible land characteristics and socio-economic factors, coupled with the impact or benefit for the environment of crops production chain, it will produce reliable maps, more than increasing the complexity of tools and methods, as also suggested by (Kalogirou 2002).

Classification issue

Classification it is used at several level in this study at it represents an important determinant that can also modify results. As defined, the method requires classification operation of the vulnerable score of each single vulnerability or comprehensive vulnerability maps. Allocation risks values of crops are also classified respect to the most impacting scenarios. Changing min e max values of classes, results in different vulnerable land extensions or in different allocation risk level for a crop in a specific location. Several approaches can be used to classify values. Within ArcView3.2 legend editor there is the possibility to define number of classes and the classification methods, i.e. equal area, equal interval, natural breaks, quantile, standard deviation. Different methods brings to different results.

The classification criteria must be chosen carefully based on specific goals and circumstances of the case. For example, if the main purpose is to emphasize the differences within the territory, the more appropriate criteria is to maintain similar amplitudes in the extension of classes (equal interval). However, if the main task is to minimize the impact of crops to the environment, a precautionary approach can be selected, increasing for example the range of the high vulnerability class.

Subjectivity of choices

The originality of the method and the absolute lack of literature often obliges to remedy with subjective criteria, such as in the elaboration of vulnerability maps, which makes the method certainly rebuttable and the results questionable. Different variables may be used to define the land vulnerability. The choice of land variables and the score assigned to each map attribute is arbitrary and it greatly influences the vulnerability level and area extent. In the literature, the aspect that links specific environmental vulnerability to a specific impact, at least as indented in LCA procedure, is still missing. In some cases, it is possible to find some studies that can be adapted to the proposed methodology, in particular for the definition of land vulnerability maps. For example the use of information and the methodology reported in the Plan for protection of Water (Severi and Bonzi 2008) were very useful in this study in defining both the vulnerability to eutrophication and to fresh water toxicity. That study are not anyway available everywhere, or they could be defined using different methods. For some impacts, as for example eutrophication, one of he most important aspect in agriculture, maybe models (Velthof, Oudendag et al. 2009) and studies that want to define the vulnerability of the territory may be more presents, and also for larger scale level, e.g. EU level. For example some information can be extracted by the EU Nitrate Directive (91/976/EC) which required member to target measures to reduce agricultural nitrate within areas vulnerable to nitrate pollution, known as Nitrate Vulnerable Zones. These Nitrate Vulnerable zones can be applied in studies that want to relate the impact to the environment ((Smith, Smith et al. 2004); (Lake, Lovett et al. 2003)). When dealing with higher spatial details, anyway, this map will be not enough to emphasize site-specific differences. Moreover, it must be realized that often the choice of factors is determined by the available information in digital format and not only by their actual importance in determining the impact.

Subjectivity can be also found in defining classes of vulnerability and for the allocation risk classes or when defining the importance of each land factor affecting the vulnerability. The attribution of weight to the factors influencing the vulnerability is another aspect of uncertainty that deserves discussion, even more relevant in cases of applied studies in very different territories, for which available data can be of different types. Appropriate coefficients (weighing) may be also used when in the determination of the overall impact of a crop, in the case of one impact is considered more important then another. It should be emphasized that the choice of weighting coefficients should be very cautious and, above all motivated by assumptions or verified by a robust literature. The use of these coefficients can indeed radically change the appearance of a map of vulnerability or of the environmental impact of a crop in a specific location. Weighting coefficients, all subjective choices, can be employed at the end in the following cases:

- attribution of risk values to the environmental factors that helps to define the vulnerability (the subjective attribution of the different values of risk corresponds to an assignment of different weights to different environmental variables);

- integration of multiple vulnerability maps, in the case of SAM and AMCM, to emphasize the land sensitivity to a particular environmental impact;

- integration of multiple indicators of impact (to emphasize an impact category).

In general, if the vulnerability to a particular environmental impact is considered as a priority, for consistency, also the corresponding LCA impact category of the crop production chain should be appropriately weighted.

It is correct, at this preliminary stage of the LCA-GIS method definition, to propose basic criteria to be followed, whenever possible, for the elaboration of vulnerability maps that can be compared and exported to other situations.

Maximum transparency it must be maintained, justifying as much as possible choices in order to ensure full traceability of the results.

The definition of a standard methodology to provide consistent vulnerability maps for all impact categories and also for their integration is required. Vulnerability has to be as much as possible related to measurable, not subjective and broadly available land information, thus to allow the reproducibility of the analysis.

In general in the whole LCA field of study, the standardization is one of main topic still under development and it will be one of principal aspects of future studies.

6. Prospects on applications

Integration of the ‘environment-to-crop’ oriented approach within land suitability (the bidirectional approach)

LCA-GIS tool for the sustainability assessment of current land use

Guideline for developments of new policy for crop chains introduction in rural areas. Crop yield or environmental impacts ?

Decision Support Systems based on Open-sources GIS

Highlights

The crop impacts can be easily integrated into existing land suitability procedures. Data on the current land use may be related with the vulnerability map and thus to know where land use can be modified in order to increase the environmental sustainability. E.g. the data showed that in the Bologna plain, 7820.80 ha of summer crops (which includes maize) are in highly vulnerable lands. This portion may be substituted with low impacting energy crops in order to increase the sustainability. Minimize the environmental impact with crop allocation, could not potentially be the best choice also from the economic point of view, but it can be supported if an economic value will be given to the environmental protection level of alternative land uses. Integrate socio-economic models with the LCA-GIS approach will represent a Decision Support System to be applied under a sustainable planning strategy in rural areas.

Integration of the ‘environment-to-crop’ oriented approach within land suitability (the bidirectional approach)

The concept of dealing with environmental impact can be integrated with the procedures generally used in land suitability studies. The impact of the crops can be considered at the same level of a soil or a climate variable and therefore can be easily integrated into existing procedures followed to build a suitability map.

As already seen in more detail in chapter 2 “Baseline principles”, even when using a multicriteriale approach in land suitability studies for novel crops, the approach is generally environment-to-crop oriented. Usually the territory is characterized in terms of pedo-climatic conditions and the crop are located where the environment is able to satisfy crop needs, e.g. as the approach followed in the work of Fiorese et al. (Fiorese and Guariso 2010). This approach is mainly linked to ensure the maximum potential yield and agronomic management, that may be linked to an economic sustainability.

Extending the criterion for allocation to the environmental impact of crops means to include a new direction in the method: not only a crop may be distributed basing on the capacity of the location to satisfy his needs, but also based on the impact of his production chain on the environment. Taking in the consideration the environmental impact of crop production chains introduce the environmental sustainability to the economic ones. The integration of this two approaches defines a bidirectional method between crop and environment (effect of environment on crop and the effect of crop chain to the environment) that increase the reliability on land suitability studies of novel crops.

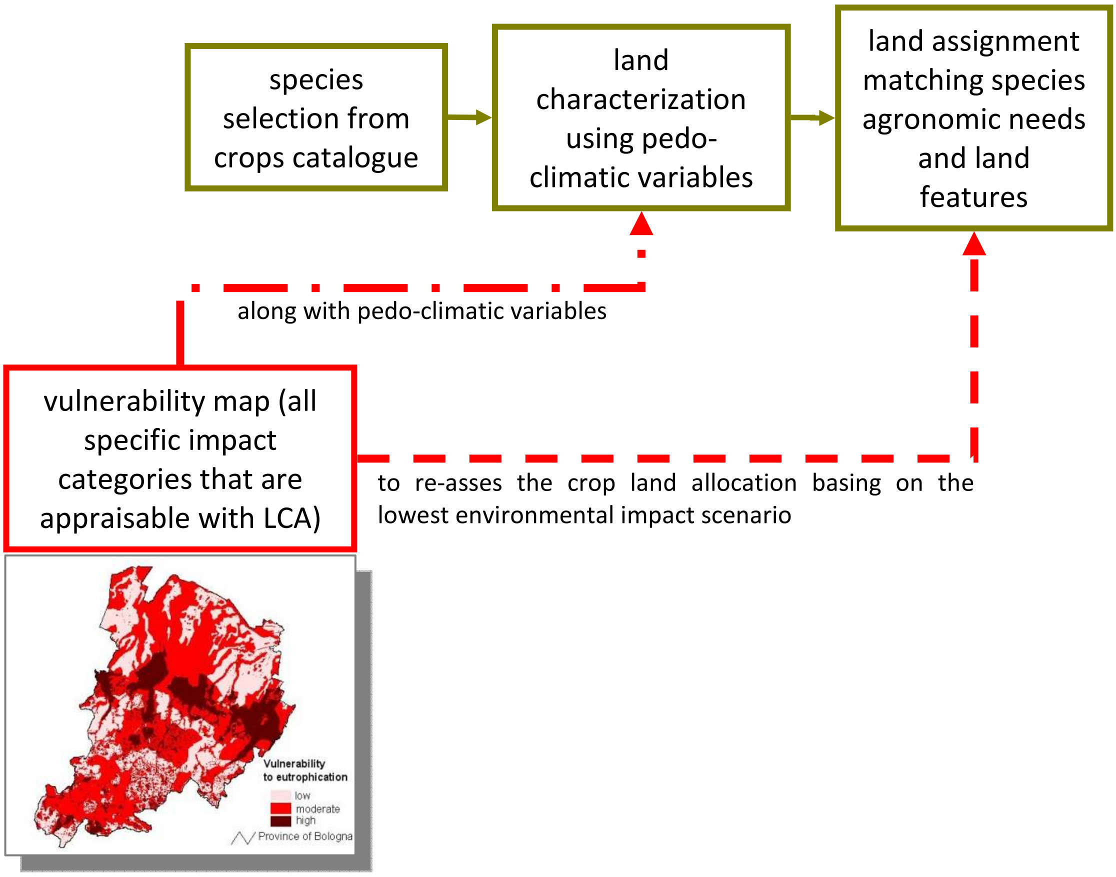


Figure 6.1. Integration of the LCA-GIS approach with land suitability studies.

The integration of the crop to environment approach may occur at different stages of a land suitability study. The effect of the crop on environment resembles a pedo-climatic variable. As it is shown in fig. 6.1, vulnerability maps (to one single impact indicator or comprehensive maps) may be considered as a pedo-climatic factor and then used at the same level in assigning suitability scores to be added to the other land characteristics in a topological overlay. High vulnerability score will of course decrease the suitability of a location to a given crop. A complete vulnerability map can be produced overlaying all specific impact categories with local effects that are appraisable with LCA (erosion risk, water consumption, etc.), and then using this map in the land characterization along with pedo-climatic variables. In other words, optimising the land assignment considering an additional variable which is the crop effect on environment.

Another approach it could be to re-asses crop land allocation defined using pedo-climatic conditions. After crops have been allocated in order to maximize their potential yield, the distribution may be adjusted considering their site specific impact, while trying anyway to conserve sustainable yields level. In other words, optimizing the land use on the base of productivity, and then using the vulnerability map to re-asses the crop land allocation basing on the lowest environmental impact scenario.

Optimize the land assignment considering an additional variable which is the crop effect on environment increases the overall sustainability level between the land use and the environment. The importance of this approach could be emphasized in the future and gaining more and more importance if an economic value will be given to the environmental protection level of land uses, a not remotely possibility looking at future agricultural policies developments (e.g. EU Commission, 2009/30/EC).

A land suitability study following the environment to crop approach requires a deep investigation of several pedo-climatic variables that is not among the targets of this study. Anyway, a simple and fast method to locate crop based on their productivity and their suitability to be grown with sustainable agronomic practices it should be to select agricultural lands from the land use map where herbaceous crops are grown. In these areas, eventually herbaceous energy crops could be easily and readily integrated with existing crop rotation as agronomic skills and facilities to manage herbaceous crops are already used. The integration of poliennal herbaceous energy crops requires a longer planning strategy, but anyway, from the pedo-climatic point of view, they could be generally suitable where herbaceous crops of the province of Bologna are already grown.

Following the selected land uses from the Land Use map (2008) that may be interested by novel herbaceous energy crops. Within ArcGis3.2, using the select by query tool, it is possible to extract that categories from the whole land use map and convert them to a new map layer.

Ultimately, selected lands represents all agricultural lands where agriculture is a normal practice. Among selected land uses, categories as orchards, or semi-natural forests, semi-natural lands or stable meadows area, anyway among agricultural lands, could be also included in order to the leave opened the possibility of a longer time planning strategy.

The province of Bologna covers about 370000 ha of which, according to the exclusion criteria used, about 237500 ha are suitable or potentially suitable for cultivation, within a brief or longer term planning strategy.

A subsequent operation called 'dissolves' has made it possible to classify all the polygons of the map in only two categories, as suitable or not for the cultivation (fig. 6.2).

LAND USE map 2008 - Land use Legend of Agricultural lands.
2 Agricultural lands .
2.1 Arable land
2.1.1.0 Non-irrigated arable areas (Sn)
Are considered non-irrigated perimeters those located in hilly and mountainous areas where irrigation is not practiced.
2.1.2 Arable crops in irrigated areas
Crops irrigated periodically or sporadically, usually with permanent structures.
2.1.2.1 Arable simple (If)
2.1.2.2 Nurseries (Sv)
2.1.2.3 Horticultural crops in open fields, greenhouses and under plastic (I know)
2.1.3.0 Rice (Sr.)
2.2 Permanent crops
Not subject to rotational crops that provide more crops and occupy the land for a long period prior to the burglary: it is mostly woody crops. Excluded are meadows, pastures and forests.
2.2.1.0 Vineyards (CV)
Areas planted with vines.
2.2.2.0 Fruit trees and berry minor (CF)
Plants trees or shrubs bearing. The fruit that is less than 1.5 ha, including agricultural land (arable land or meadows) are considered important in the class 2.4.2. The presence of orchards with different groups of trees are included in this class.
2.2.3.0 Groves (Co)
Areas planted with olive trees, including particles in mixed cultivation of olive trees and vines.
Arboriculture for wood
2.2.4 Area planted with trees of forest species for fast-growing timber production operations are subject to an agricultural crop.
2.2.4.1 poplar cultivation (Cp)
2.2.4.2 Other crops from wood (walnut forests, etc..) (Cl)
2.3 Meadows Stable
2.3.1.0 stable Meadows (PP). Surfaces to dense herbaceous cover, mainly represented in the floristic composition of grasses, not subject to rotation.
2.4 Heterogeneous agricultural areas
2.4.1.0 Temporary crops associated with permanent crops (Zt)
Annual crops (arable land or grassland) in association with permanent crops on the same surface. There are mixed areas of crops including temporary and permanent when the latter accounting for less than 25% of the total area.
2.4.2.0 Cropping systems and particle complexes (Zo)
Patchwork of individual plots is not temporary maps with various crops, permanent grassland and permanent crops occupying each less than 50% of the mapped element (eg vegetable gardens for seniors).
2.4.3.0 areas predominantly occupied by agriculture, with important natural spaces (Ze). The crops occupy more than 25% and less than 75% of the total area mapped element. The natural areas can be represented by hedges, bushes, patches of tree line.
3 the forest and semi-natural environments
3.1 wooded areas
3.1.1 Broad-leaved forest
Plant formations, consisting mainly of trees, bushes and shrubs but also, in which species dominate the hardwood forest. The hardwood surface is at least 75% of the component tree forest, otherwise it is classified as mixed forest.

3.1.1.1 Forests consisting mainly of beech (Bf)
They are usually located in an altitudinal range of more than 900 meters above sea level
3.1.1.2 Forests consisting mainly of oak, hornbeam and chestnut (Bq)
They are usually located in a strip less than 900 meters altitude above sea level
3.1.1.3 Forests consisting mainly of willows and poplars (BS)
They consist of hygrophilous species usually present in areas with plenty of water.
3.1.1.4 Woods in flat areas with prevalence of oaks, ash, etc.. (BP)
3.1.1.5 chestnut (Bc)
Areas with chestnut trees which are regularly carried out activities of pruning and cleaning of the undergrowth.
3.1.2.0 Coniferous forest (Ba)
Plant formations consist mainly of trees, bushes and shrubs but also in which coniferous forest species dominate. The area is at least 75% conifer component of the forest tree, otherwise it is classified as mixed forest.
3.1.3.0 Mixed woods of conifers and deciduous trees (WB)
Plant formations, consisting mainly of trees, bushes and shrubs but also, where neither deciduous nor coniferous exceed 75% of the component tree forest.
3.2 Environments with shrubbery and / or herbaceous evolving
3.2.1.0 Grasslands and heath at high altitude (Tp)
Areas with natural vegetation to herbaceous or low-shrub, located above the limit of natural vegetation and trees in the Emilia-Romagna region is located between 1400 and 1600 meters above sea level
3.2.2.0 bushes and shrubs (Tc). Low and closed vegetation formations, mainly consisting of bushes, shrubs and herbaceous plants.
3.2.3 Areas to shrubbery and trees changing
Shrubby or herbaceous vegetation with scattered trees. Formations that may result from the degradation of the forest or renewal of same for recolonization of areas adjacent to non-forest or forest areas. Differ from 3.2.2.0 to the particular situation of location (eg. Former agricultural land with terraces or particle boundaries) or in relation to time parameters-cultural-specific environmental (eg. Burned areas or subject to damage of various kinds and origin).
3.2.3.1 Areas with shrub vegetation and / or grass with scattered trees (Tn)
3.2.3.2 Areas with recent forestation (Ta)
3.3 open areas with little or no vegetation
3.3.1.0 beaches, dunes and sands (DS)
There are including beaches, dunes and expanses of sand and pebble beaches and continental environments. The dunes covered with woody or herbaceous vegetation are classified in entries 3.1 and 3.2.
3.3.2.0 bare rocks, cliffs and outcrops (Dr)
Areas with vegetation cover less than 10%.
3.3.3 Areas with sparse vegetation
3.3.3.1 ravines Areas (DC)
3.3.3.2 Areas with sparse vegetation and other (right). Areas where vegetation cover is between 10% and 50%.
3**.3.4.0 Areas covered by fire** (a) .Or semi-natural woodlands affected by recent fires. The charred material are still present.

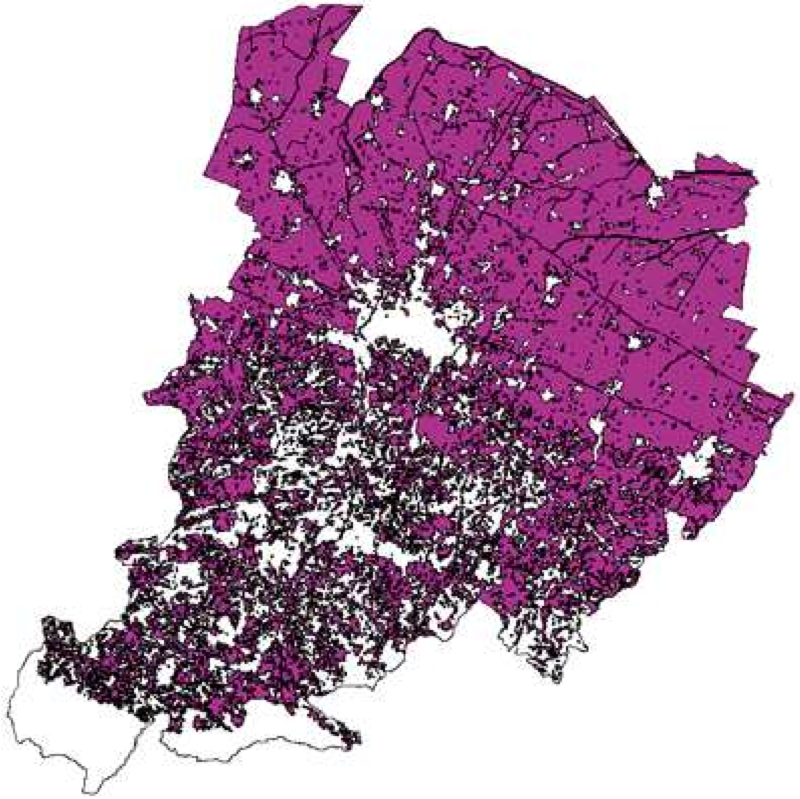


Figure 6.2. Agricultural lands extracted from the Land Use map (2008). These areas may be considered as suitable for the cultivation of energy crops or for a re-assess of the land use in order to maximize its sustainability.

LCA-GIS tool for the sustainability assessment of current land use

The vulnerability map provides direct information on the real capacity of the area to cope with the impacts generated by different types of crops and cultivation schemes. The link of the vulnerability map with the current land use may represent a tool to understand its sustainability. From the inventory of cultivated crops in a given area and the quantification of their impacts (using LCA approach), it is possible to understand for example whether and in what proportion the highest impacting crops are grown in areas classified with low or high vulnerability, and consequently, if possible, with the use of territorial planning tools to re-allocate crops in order to minimize the risk for the environment. As a general rule, ideally, the crop with the highest impact should be grown on less vulnerable areas, and vice versa. Currently, there are lot of political and economic constraints which hinders this principle, and of course this principle is more ease to implement in a developing area respect to regions with a well established agriculture. However, in a context in which sustainability is recognized and driven by fiscal policy, this principle may also assume and economic value, as well as social and environmental. This hypothesis is not so far given the increasing socio-political perceptions towards environmental issues.

When studying the impact of the current land use on environment, the first problem is encountered when searching for the availability of detailed maps of crop locations. Information of this nature are unfortunately not easy to find, especially at a high level of detail as, for example, the single field or farm. In the case of herbaceous annual crops this appears partly explained by the fact that they usually are part of the crop rotation and rarely they are grown on the same field for several years. Again their cultivation is also more directly subjected, respect to tree crops, to the trade demand and prices, resulting in unstable cultivation during years. Usually high resolution surveys on the crop presence are expensive operations that are not frequently carried out.

Much easier is to find information at higher scale level than farm field, e.g. hectares of crops aggregated at municipal or provincial level, or when crops are aggregated in categories, e.g. herbaceous, tree crops, fallow lands, etc.

Some information about the crop distribution in the province of Bologna may be obtained by the Land Use map of the Emilia Romagna region, released by the Emilia Romagna regional office, and which his last version is updated at 2008. This map is obtained from remote sensing image interpretation. As a map, it indicates the location of crops, thus the spatial resolution of the information is not linked to administrative borders (municipalities, provinces, regions, etc.), that is usually the data format aggregation which data are released for example by statistical sources, and they may be spatially related to the site-specific vulnerability of the case study area.

In the Land Use map, the territory is hierarchically classified in categories and sub categories. Concerning agricultural lands, that are part of the category named “lands modified by humans”, at the base of the hierarchical classification, i.e. the higher detail, the territory is classified in the following categories:

1. SN - Annual herbaceous crops in not-irrigated lands. Not irrigated lands are hilly and mountainous areas of the region, where the irrigation is not generally carried out and where there are not stable infrastructure to support irrigation)
2. SI - Simple annual herbaceous crops in irrigated lands. Crops irrigated continuously or occasionally thanks to the presence of stable irrigation infrastructures.
3. Nurseries.
4. Horticultural crops in open fields, in greenhouses or under tunnels.
5. Rice fields.
6. Poliennal permanent crops. Crops not included in the rotation scheme, harvested for several years in the same field before ploughing. Generally tree crops as fruit crops. Not including meadows, pastures and forests.
7. Vineyards.

Among the above listed Land Use map classifications, maize and wheat, two crops currently grown in the province of Bologna and taken under consideration in this study, fall within the categories 1 and 2 (SN and SI), arable lands in irrigated and not irrigated areas. Maps of fig. 6.3 reports localization of sowable irrigated (SI) and sowable not irrigated (SN). Irrigated lands are in the Northern part of the province, corresponding with the flat area with specialized agriculture. In practise, this area is completely provided by stable irrigation infrastructures. Non irrigated lands are in the hilly and mountainous part of the province, where irrigation it could be possible but it is not a routine practice.

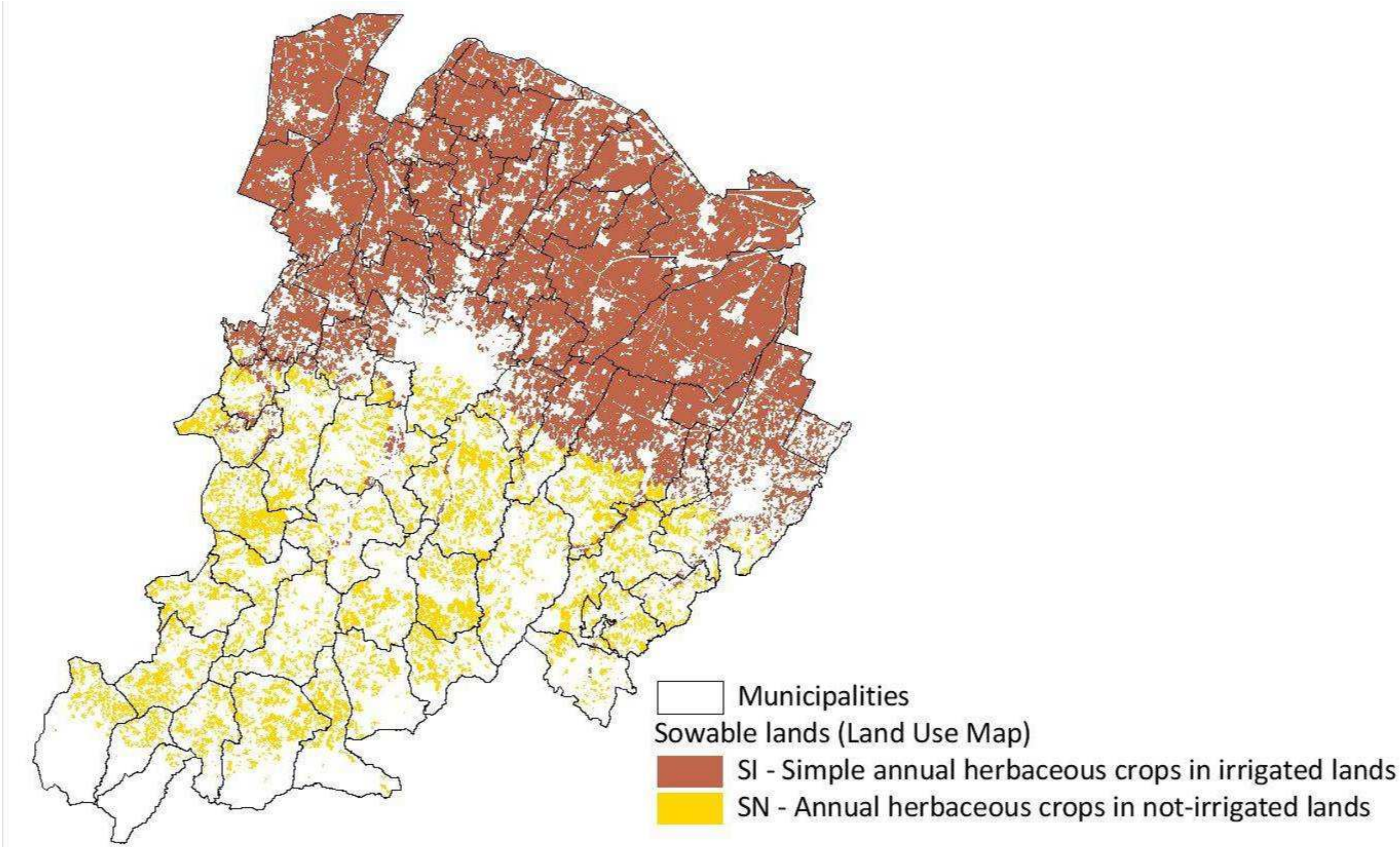


Figure 6.3. Sowable lands from the Land Use Map (2008) in the province of Bologna.

For this two crops aggregation, it is possible to know their impact on the base of the vulnerability of the case study area. In fig. 6.4 it is reported the comprehensive allocation risk for maize, referring to FWT, EU and HUMT, calculated following the CMM of classified maps.

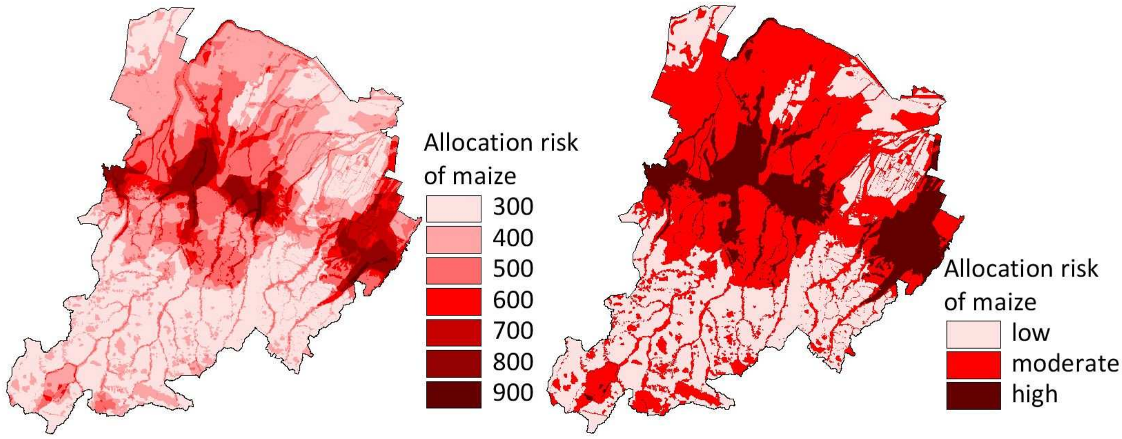
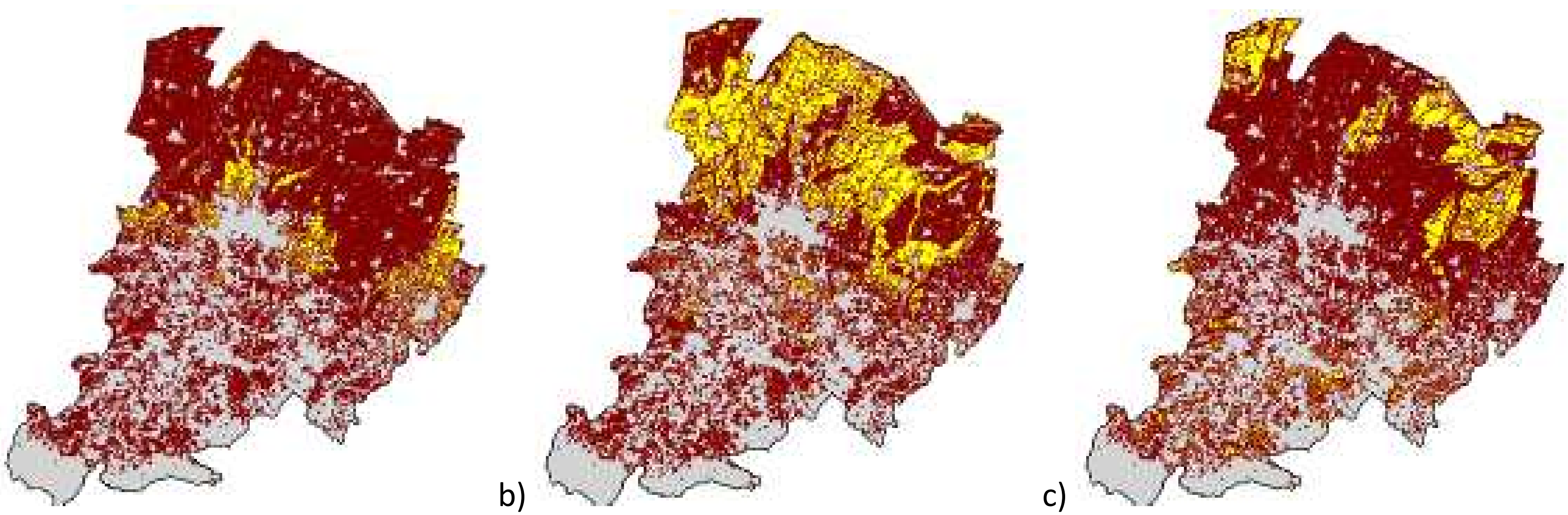


Figure 6.4. Allocation risk for maize in the province of Bologna (3 impact indicators and CMM of classified maps).

Through a selection query in ArcView3.2 of irrigated and not irrigated arable lands (category 1 and 2 of the Land Use Map) and of their topological overlay with the vulnerability map of fig. 3.9, is it possible to define selected arable lands that are classified as low, moderate or high vulnerable. In fig. 6.5, the polygons indicate arable (irrigated or not) in the province of Bologna, and in yellow portions located in the high, medium and low risk of allocation for maize. Overlaying arable lands with the impact map for maize, polygons representing the arable land are split at the vulnerability borders of map 6.4.



a) b) c)

Figure 6.5. Annual herbaceous crops (in irrigated and not irrigated lands in the province of Bologna (source: Land Use Map, 2008). In yellow, areas located in high (a), moderate (b) and low (c) allocation risk lands, respect to maize.

At each new polygon can be assigned the vulnerability level information in a new attribute field of the associated database. Within ArcView3.2, area extensions and percentages can be calculated (table 6.1 3.5).

Table 6.1. Area extension (ha) of sowable lands (in irrigated and not irrigated areas, from the Land Use map 2008) split based on the allocation risk for maize in the province of Bologna. Percentages refer to the row total.

Land use extension (ha)	Allocation risk			
	low	moderate	high	total
SI - sowable irrigated	30252.1	78800.96	26059.45	136112.5
SN - sowable not irrigated	24124.66	16180.25	1962.8	42267.71
total	54376.75	95981.22	28022.25	178380.2
%				
SI - sowable irrigated	22.2	58.6	19.2	100.0
SN - sowable not irrigated	57.1	38.3	4.6	100.0
total	30.5	53.8	15.7	100.0

In the province of Bologna, 15.7 % of annual herbaceous crops are located in lands with high allocation risk for maize, 53.8 % in lands with a moderate risk and 30.5 % in the low allocation risk areas (table 6.1).

Although land use map does not indicate exactly single crops, but they are aggregated in the two categories SI and SN, there is a high probability that they include corn or wheat, two main crops in the province.

The actual area of corn, wheat or other crops is still traceable from other sources, such as the Statistical Office of the Emilia Romagna (StatisticaE-R) who emits each year estimates on the base of agrarian regions (fig. 6.6). The territory of Emilia-Romagna Region is subdivided into 9 Provinces (NUTs3) and 341 municipalities. In addition, there are subprovincial territorial units called agrarian regions (46 in total) that group several municipalities of a given province (on average 7 municipalities each agrarian region) to define somewhat homogenous regions from the agricultural perspectives and for which statistics are normally published. In the province of Bologna there are 8 agrarian regions (table 6.2).

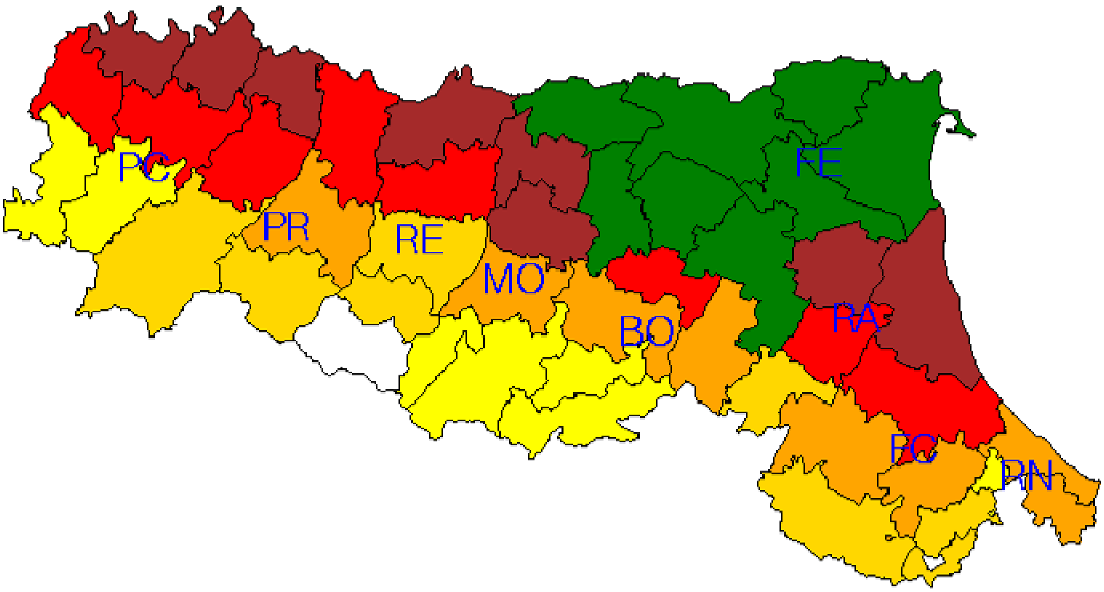


Figure 6.6. Agrarian region aggregations in the Emilia Romagna region.

Table 6.2. Municipalities of the agrarian regions in the province of Bologna.

Agrarian region	Municipalities
Regione Agraria n.1 – Montagna del Medio Reno	Castel d'Aiano, Gaggio Montano, Grizzana Morandi, Monzuno, Vergato
Regione Agraria n.2 – Alto Reno	Camugnano, Castel di Casio, Castiglione dei Pepoli, Granaglione, Lizzano in Belvedere, Monghidoro, Porretta Terme, San Benedetto Val di Sambro
Regione Agraria n.3 – Colline di Bologna	Bologna, Casalecchio di Reno, Ozzano dell'Emilia, San Lazzaro di Savena, Zola Predosa
Regione Agraria n.4 – Colline del Reno	Bazzano, Castello di Serravalle, Loiano, Marzabotto, Monte San Pietro, Monteveglio, Pianoro, Sasso Marconi, Savigno
Regione Agraria n.5 – Colline del Sillaro e del Santerno	Borgo Tossignano, Casalfimanese, Castel del Rio, Castel San Pietro Terme, Dozza, Fontanelice, Monterenzio
Regione Agraria n.6 – Pianura a sinistra del Reno	Anzola dell'Emila, Calderara di Reno, Crespellano, Crevalcore, Sala Bolognese, San Giovanni in Persicelo, Sant'Agata Bolognese
Regione Agraria n.7 – Pianura a destra del Reno	Argelato, Baricella, Bentivoglio, Castello d'Argile, Castel maggiore, Galliera, Granarolo dell'Emilia, Malalbergo, Minerbio, Pieve di Cento, San Giorgio di Piano, San Pietro in Casale
Regione Agraria n.8 – Pianura dell'Idice e del Santerno	Budrio, Castel Guelfo, Castenaso, Imola, Medicina, Molinella, Mordano

The boundaries of agrarian regions follow with good approximation the boundaries that define the irrigated and non-irrigated arable lands, for which it was possible to calculate the actual values of single crops in SI and SN arable lands, keeping separated the two types of soils, irrigated and not irrigated (table 6.3).

In the whole province, the 14.6 % of the sowable lands is represented by maize, 49.02 % by wheat and 1.28 % by sunflower. Among cereals, wheat is most represented crop, both in irrigated lands (48.76 % of irrigated lands) and in no-irrigated lands (51.07 % of no-irrigated lands).

After all the dislocation of crops in the province is not so far in assisting the vulnerability of the territory. Using land use maps, 19.2 % of irrigated lands are located in highly vulnerable areas and of this portion, only 16.05 % is represented by maize; it must be said, however, that for obvious reasons maize is far more present in the irrigated areas (16% of irrigated areas are covered with maize) and much less in non-irrigated (3.4% of total non-irrigated lands).

Table 6.3. Presence in hectares and as % of some interesting crops related to this study located in the province of Bologna. (Source: data elaboration from aggregated statistical data 2008 on the base of agrarian regions. Percentage is respect the row total).

Land use	SI - sowable irrigated (ha)	SN - sowable not irrigated (ha)	Total sowable in the Province (ha)	SI - sowable irrigated (%)	SN - sowable not irrigated (%)	Total sowable in the Province (%)
cereals	67902	9572	77474	78.72	85.84	79.54
wheat	42055	5695	47750	48.76	51.07	49.02
maize	13844	376	14220	16.05	3.37	14.60
sunflower	982	268	1250	1.14	2.40	1.28
rapeseed	207	13	220	0.24	0.12	0.23
sugarbeet	8530	403	8933	9.89	3.61	9.17
tot	86255	11151	97406	100	100	100

Basing on these conclusions, maize portion in high vulnerable lands could be reallocated in lower vulnerability lands.

Regarding wheat, his presence in the territory is higher respect to maize and when considering multiple impact indicators, his allocation risk resulted comparable with maize. This means that maybe also wheat could be re-allocate in lower vulnerable areas in order to increase land sustainability.

The decision maker must evaluate on the one hand the disadvantages on eventually yield reduction, and secondly, the environmental benefits deriving from a more efficient allocation of maize, or of wheat, in an environmental key. The substitution of these food crops with some herbaceous perennial as switchgrass in vulnerable lands will reduce the overall land use impact. It is clear that the balance between food and no-food and the economic value attributed to the environmental benefits can act as a factor in selecting the planning strategy.

More information on the actual land use and crops distribution can also be obtained by processing the results of the COLT project (crop classification through remote sensing) (Spisni and Mariani 2010), co-funded by the Regional Environmental Agency (ARPA) and the Department of Agriculture of Emilia-Romagna region. COLT project is a tool for spatially detection and crop quantification through photo-interpretation and analysis of multitemporal series of remote sensing images acquired by satellite. Acquisitions are scheduled during the period between November and June. The tool's mission is primarily to address the estimation of water needs by integrating models on water use and crop growth, and consequently the planning of water delivery in agriculture during the upcoming growing season. Main used model is the regional idrological model called CRITERIA (Marletto, Zinoni et al. 1993). Data are available each year at June. The project beneficiaries are principally Irrigation Consortiums of Emilia-Romagna region. The study area covers only the flat area of the region, which is the area where Irrigation Consortiums act, also representing the more intensive agricultural area in the region. The study area also coincides with the sowable lands in irrigated areas of the Land Use map 2008 (fig. 6.5). Crops are classified into aggregated categories of crops, linked to the ability to differentiate the crops basing on their phenology and how their appear in the remote sensing image at different times of the growing cycle. Categories are reported in fig. 6.7, which shows the location of different groups of crops on the province of Bologna’s plains.

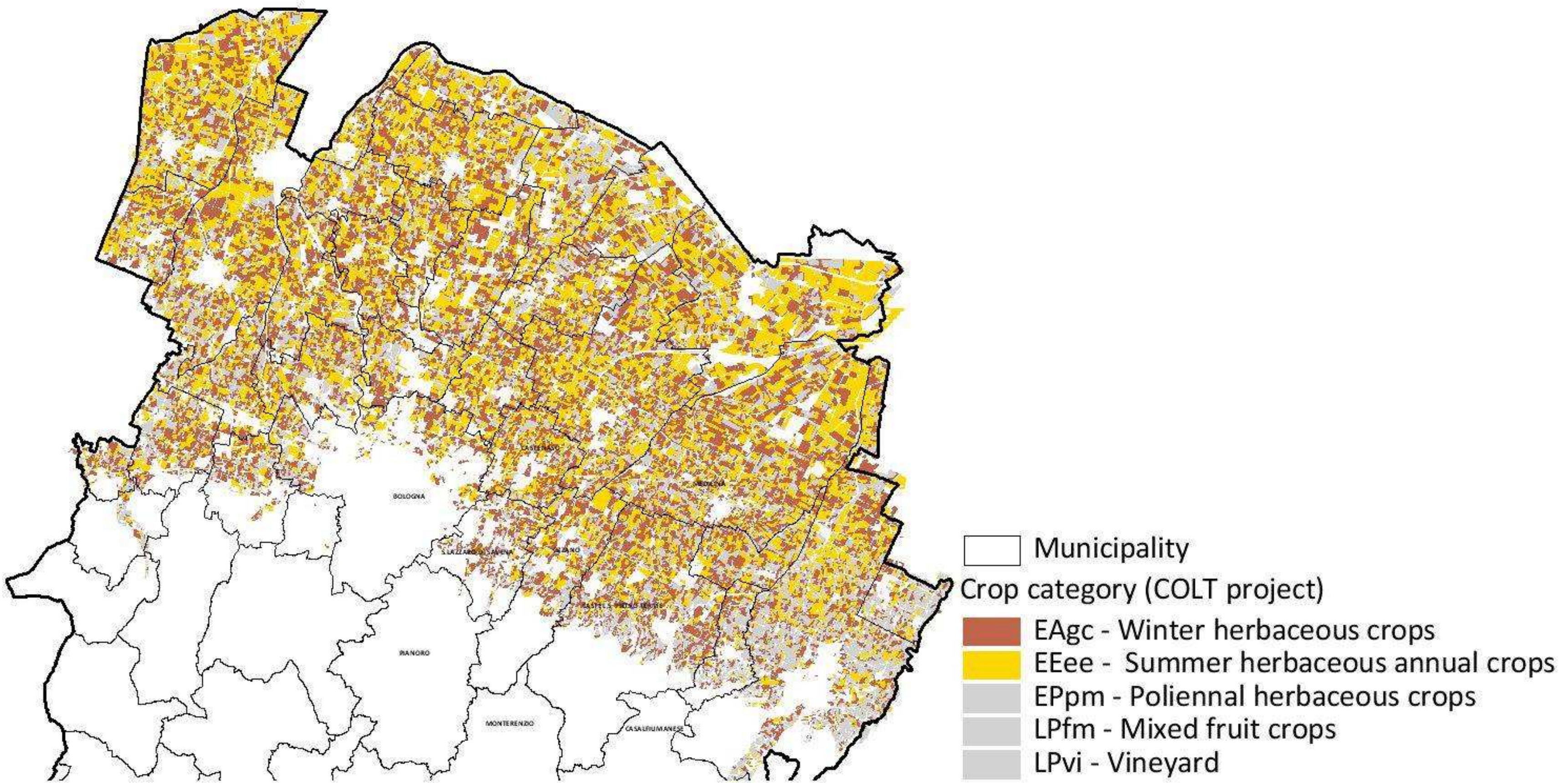


Figure 6.7. Crops categories distribution in the flat valley of the province, data elaboration from COLT project (growing seasons 2009-2010). Winter crops are mainly represented by wheat; summer crops includes maize.

Project COLT ‘s maps have very high level of spatial resolution, allowing to identify the land use next to each farm field level, and for this reason is particularly appropriate for the comparison with vulnerability and allocation risk maps.

Crops included in the 2010 aggregation are:

- 1.EEee. Summer herbaceous annual crops (corn, sugar beet, sunflower, sorghum, potato, tomato, soybean, uncultivated, carrot, onion, cilantro, fresh beans, lettuce, melon, pea.)
- 2.EAgc. Winter herbaceous crops (cereals, wheat, barley, rye, grass hay and rapeseed)
- 3.EPpm. Poliennal herbaceous crops (pasture and alfalfa)
- 5.EEri.Rice (from land Use Map 2008)
- 12.LPvi.Vineyard (from land Use Map 2008)
- 13.LPfm. Mixed fruit crops (from land Use Map 2008). Includes apple, kiwi, peach, pear and other fruits.
- Clouds
- ND. Missing area.

Among identified categories, the following are of interest for the comparison with the vulnerability map:

- EAgc - Vernine autumn crops: wheat, barley, rye, rapeseed;
- EEEE - Summer crops: corn, sugar beet, sunflower, sorghum, potato, tomato, soybean, uncultivated, carrot, onion, cilantro, fresh beans, lettuce, melon, pea.

COLT’s project, as for data coming from the Land Use map, is not able to identify individual crops, such as corn and wheat. However, it is possible to calculate the presence of corn and wheat with a good approximation linking the two main categories EAgc and EEEE with other databases such as, for example, the Agriculture censuses by ISTAT (the Italian institute of Statistics), which provide the most updated data source of available at municipal level, the greater detail in which data are distributed.

Topological overlay of the map elaborated starting from COLT data (fig. 6.7) with those of the environmental impact of the crops, e.g. maize (fig. 6.4), allows to identify land uses portions that fall in areas with high, medium or low environmental risk (fig. 6.8 to 6.10). The processing of these maps in ArcView3.2 also allows to extract various additional information such as extensions in hectares and crops located on the different vulnerable land portions (table 6.4).

Table 6.4. Crop categories surface extension (ha) from elaboration of COLT project's data split in the 3 allocation risk classes (low, moderate and high) on the base of the comprehensive vulnerability map of the province (3 impact indicators, CMM impact integration). Percentages are respect to each row total.

Crops group	low	moderate	high	total
EAgc - Winter crops	10656.79	30326.66	10867.27	51850.71
EEee - Summer crops	12950.72	28569.10	7820.80	49340.62
EPpm - Grasses and alfalfa	3908.20	10747.52	3564.85	18220.58
LPfm - Tree fruit crops	1014.03	3865.49	4783.26	9662.77
LPvi - vineyards	13.42	523.48	659.88	1196.78
Total	28543.16	74032.25	27696.06	130271.46
%				
EAgc - Winter crops	20.55	58.49	20.96	100
EEee - Summer crops	26.25	57.90	15.85	100
EPpm - Grasses and alfalfa	21.45	58.99	19.56	100
LPfm - Tree fruit crops	10.49	40.00	49.50	100
LPvi - vineyards	1.12	43.74	55.14	100
Total	21.91	56.83	21.26	100

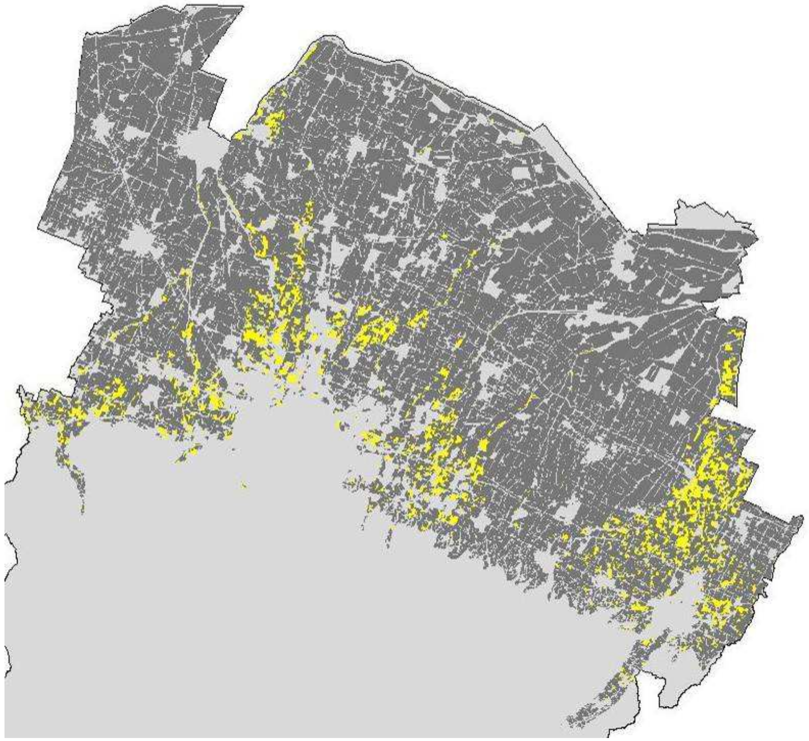
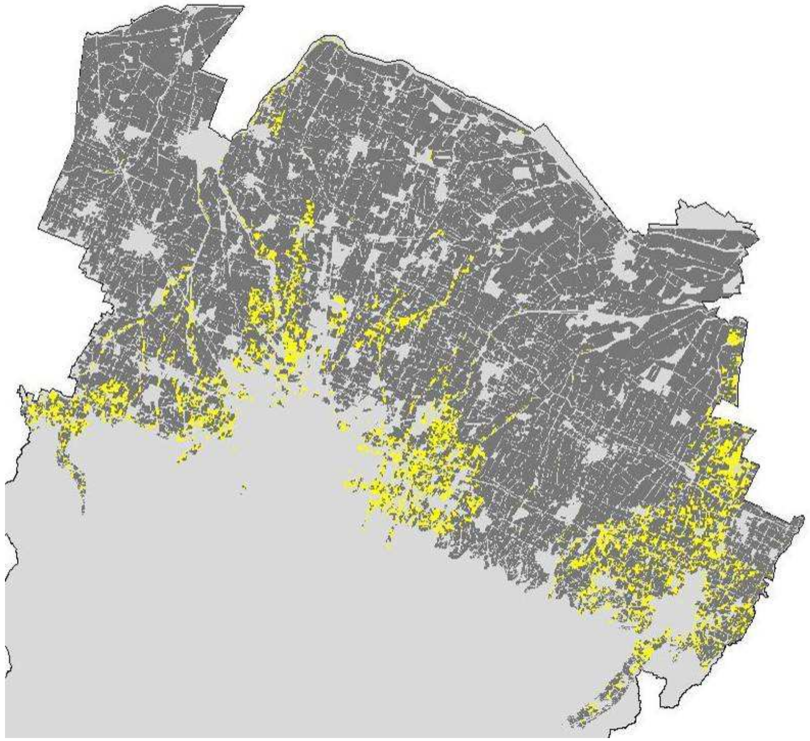
a)  b) 

Figure 6.8. EEee (summer crops) and EAgc (winter crops) location in the province of Bologna (data source: elaboration from COLT project 2010). In yellow, summer herbaceous crops (a) and winter herbaceous crops (b) located in areas with a high allocation risk.

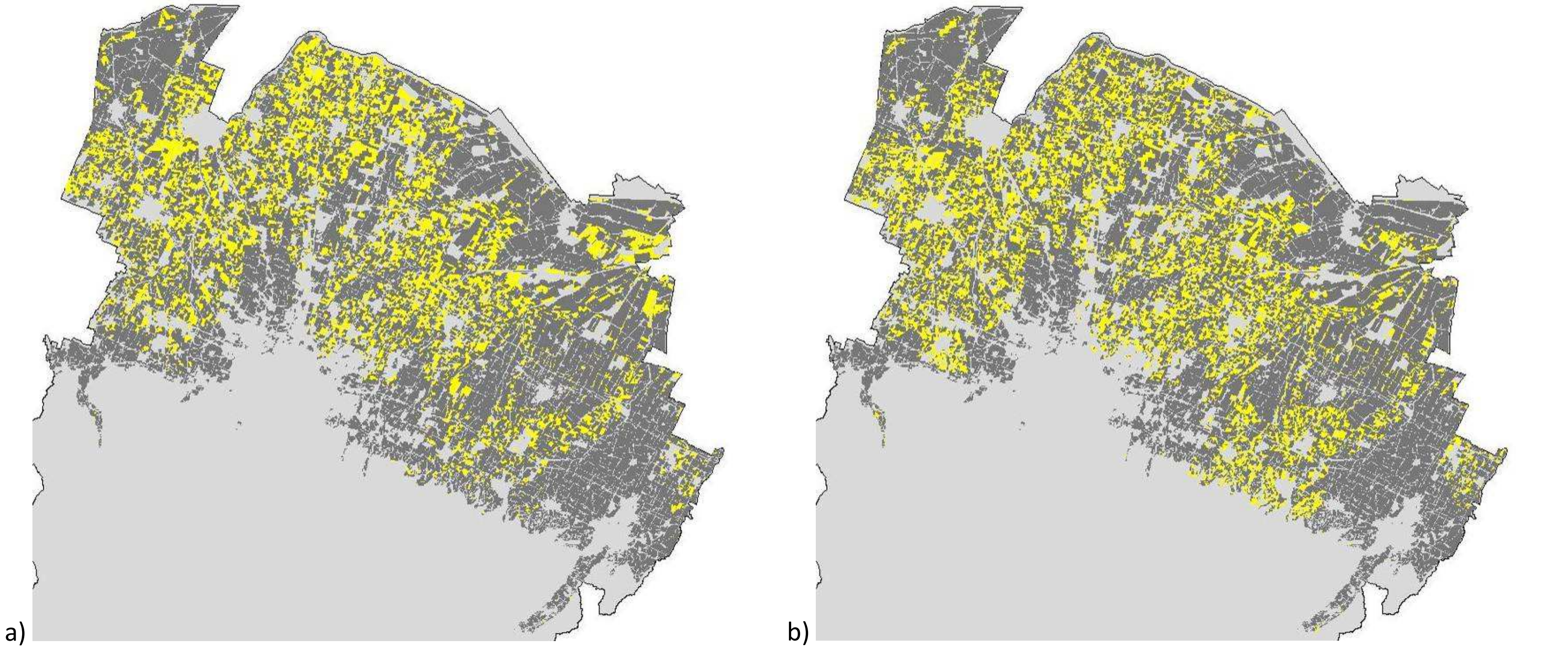


Figure 6.9. EEee (summer crops) and EAgc (winter crops) location in the province of Bologna (data source: elaboration from COLT project 2010). In yellow, summer herbaceous crops (a) and winter herbaceous crops (b) located in areas with a moderate allocation risk.

Figure 6.10. EEee (summer crops) and EAgc (winter crops) location in the province of Bologna (data source: elaboration from COLT project 2010). In yellow, summer herbaceous crops (a) and winter herbaceous crops (b) located in areas with a low allocation risk.

According to COLT’s data, in the flat area of the province of Bologna, 20.96 % (10867.27 ha) of arable winter crops (including wheat) are grown in areas classified as highly vulnerable. The data also shows that 15.85 % (7820.80 ha) of summer crops (which includes maize) are grown in areas classified as highly vulnerable (table 6.4); more than a half (approx. 58 %) of summer crops are in areas of medium impact. Values are similar to those previously calculated on the basis of the Land Use map.

It is also worth noting that half of orchards and vineyards are located in areas with high environmental risk. It is true that the vulnerability was calculated thinking of herbaceous crops and that the used vulnerability map is related to maize, from which the highest impact on the territory are identified. Maize maybe requires greater use of fertilizers, but also a lower use of chemical treatments. It would be then interesting to assess the environmental impact of orchards and recalibrate the map of vulnerability on it, in order to quantify the actual 'environmental hazard' in the current orchard locations.

ISTAT, the Italian National Institute of Statistic, with the 5th Census on Agriculture carried out in 2000, collected data of crops hectares aggregated at municipal level. Each municipality, at national scale, has an identifying unique code which is used when dataset are released. Map of fig. 6.11 reports those ISTAT codes and the correspondence with the municipality name.

ISTAT code	Municipality name	ISTAT code	Municipality name
37001	ANZOLA	37031	GRIZZANA
37002	ARGELATO	37032	IMOLA
37003	BARICELLA	37033	LIZZANO IN BELVEDERE
37004	BAZZANO	37034	LOIANO
37005	BENTIVOGLIO	37035	MALALBERGO
37006	BOLOGNA	37036	MARZABOTTO
37007	BORGO TOSSIGNANO	37037	MEDICINA
37008	BUDRIO	37038	MINERBIO
37009	CALDERARA DI RENO	37039	MOLINELLA
37010	CAMUGNANO	37040	MONGHIDORO
37011	CASALECCHIO DI RENO	37041	MONTERENZIO
37012	CASALFIUMANESE	37042	MONTE S.PIETRO
37013	CASTEL D'AIANO	37043	MONTEVEGLIO
37014	CASTEL DEL RIO	37044	MONZUNO
37015	CASTEL DI CASIO	37045	MORDANO
37016	CASTEL GUELFO	37046	OZZANO
37017	CASTELLO D'ARGILE	37047	PIANORO
37018	CASTELLO DI SERRAVALLE	37048	PIEVE DI CENTO
37019	CASTEL MAGGIORE	37049	PORRETTA TERME
37020	CASTEL S. PIETRO TERME	37050	SALA BOLOGNESE
37021	CASTENASO	37051	S.BENEDETTO VAL DI SAM
37022	CASTIGLIONE DEI PEPOLI	37052	S.GIORGIO DI PIANO
37023	CRESPELLANO	37053	S.GIOVANNI IN PERSICET
37024	CREVALCORE	37054	S.LAZZARO DI SAVENA
37025	DOZZA	37055	S.PIETRO IN CASALE
37026	FONTANELICE	37056	S.AGATA BOLOGNESE
37027	GAGGIO MONTANO	37057	SASSO MARCONI
37028	GALLIERA	37058	SAVIGNO
37029	GRANAGLIONE	37059	VERGATO
37030	GRANAROLO	37060	ZOLA PREDOSA

Figure 6.11. Municipalities in the Province of Bologna. Grey filled poligons represents urban areas.

Data from the year 2000 are available for consultation (ISTAT 2000). A specific dataset extracted from the national database was prepared and spatially linked to the map of municipalities of the province of Bologna. The dataset is shown in fig. 6.12 as map reporting hectares of maize and wheat in the municipalities. Information shown in map of fig. 6.12 can be integrated through overlaying, with sowable lands (irrigated and not irrigated) of land use maps classified based on their vulnerability (fig. 6.5). The same can be done using maps of fig. 6.8 to 6.10, reporting the classification of winter and summer crops referring to COLT project on the vulnerable lands. From the elaboration of these map overlays, data summarized in table 6.5 and 6.6, can be obtained. Since the greatest detail of ISTAT data is the municipal border, this will correspond to the resolution of the information regarding the distribution of crops in vulnerable areas.

In summary, the province comprises approximately 28000 ha of sowable lands in high vulnerability zones, of which 6.49 % are covered by corn and 29 % by wheat (table 6.5). The municipality of Imola has the highest number of hectares of sowable land in high-risk areas (8054.45 ha). However, only 3.68 % of Imola's sowable lands are covered by maize. Wheat is present in the 32.88 % of Imola's sowable lands, and as its impact could be compared to maize when considering multiple impact indicators. It could be effectively thought to partially substitute wheat or maize with lower impacting crop in order to minimize environmental impacts.

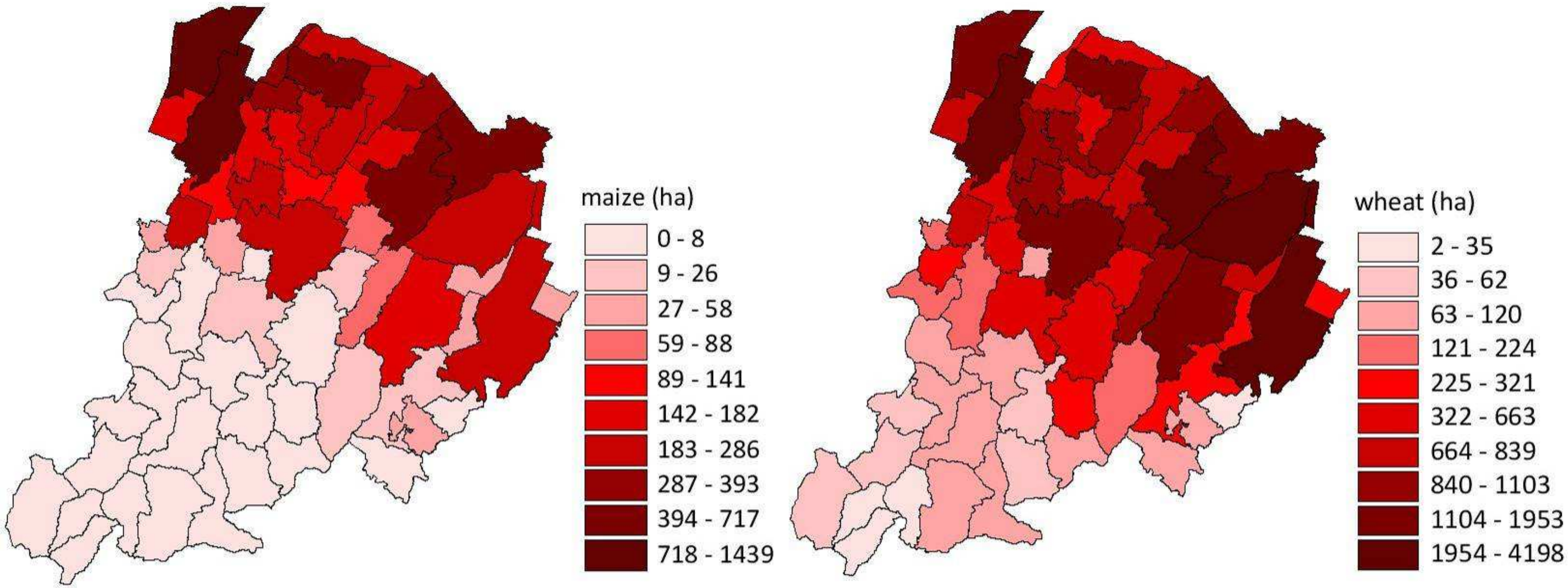


Figure 6.12. Extension of maize and wheat fields in the municipalities of the province of Bologna (source: Elaboration of the 5th Census on Agriculture, 2000).

Table 6.5. Total sowable lands (ha) from the Land Use map located in each municipality with the corresponding % of maize, wheat and sunflower (data from the 5° ISTAT Census on Agriculture). For each municipality, land portions are also classified based on vulnerability map of maize (3 impact indicators, CMM impact integration).

ISTAT code	Municipality	low	moderate	high	total	maize (%)	wheat (%)	sunflower (%)
37001	ANZOLA		2010.91	527.27	2538.18	5.79	32.23	0.06
37002	ARGELATO	0.27	1926.85	716.22	2643.34	6.14	38.49	0.00
37003	BARICELLA	3014.17	421.93	0.27	3436.38	10.33	31.35	0.15
37004	BAZZANO		0.13	850.15	850.29	6.74	22.83	3.13
37005	BENTIVOGLIO	2858.97	971.89	1.68	3832.55	10.53	35.66	0.00
37006	BOLOGNA		2202.63	1627.23	3829.86	5.10	35.72	2.43
37007	BORGO TOSSIGNANO	557.29	86.73	32.01	676.03	0.98	5.75	10.87
37008	BUDRIO	3.34	10073.72	215.23	10292.29	5.91	32.13	0.21
37009	CALDERARA DI RENO		1562.46	1481.47	3043.93	8.56	38.39	0.97
37010	CAMUGNANO	1572.34	514.64	0.29	2087.26	0.05	7.27	0.00
37011	CASALECCHIO DI RENO		209.14	268.18	477.32	0.06	24.97	3.78
37012	CASALFIUMANESE	1784.78	640.77	37.99	2463.53	0.79	13.71	1.07
37013	CASTEL D'AIANO	1056.55	165.31		1221.85	0.00	6.04	0.00
37014	CASTEL DEL RIO	535.61	164.45	0.00	700.06	0.09	13.62	2.48
37015	CASTEL DI CASIO	820.23	143.79		964.02	0.00	6.98	0.00
37016	CASTEL GUELFO	2.12	2184.26	114.77	2301.15	2.39	32.43	0.34
37017	CASTELLO D'ARGILE		2276.91	8.79	2285.70	18.26	35.54	0.00
37018	CASTELLO DI SERRAVALLE	917.25	446.75	107.52	1471.52	0.14	18.07	1.96
37019	CASTEL MAGGIORE	0.10	586.39	1540.10	2126.59	8.19	40.31	0.00
37020	CASTEL S. PIETRO TERME	2585.16	5783.42	405.44	8774.01	2.52	24.02	0.24
37021	CASTENASO		1709.58	1011.69	2721.27	3.61	39.33	0.00
37022	CASTIGLIONE DEI PEPOLI	1037.69	124.63		1162.32	0.00	12.58	0.00
37023	CRESPELLANO		1100.70	1281.66	2382.37	12.03	34.88	1.78
37024	CREVALCORE	6512.37	1828.15	0.41	8340.92	24.76	30.43	0.03
37025	DOZZA	0.28	60.20	1079.31	1139.80	3.34	25.34	1.03
37026	FONTANELICE	1108.07	72.12		1180.19	2.85	8.69	1.44
37027	GAGGIO MONTANO	1590.80	298.09		1888.89	0.00	5.63	0.00
37028	GALLIERA		2694.73	38.98	2733.71	14.88	34.53	0.06
37029	GRANAGLIONE	83.51	12.52		96.02	0.00	10.53	0.00
37030	GRANAROLO	0.83	1780.48	892.03	2673.34	5.74	32.66	0.00
37031	GRIZZANA	1122.14	213.41		1335.54	0.00	10.25	0.00
37032	IMOLA	3.90	1768.91	8054.45	9827.26	3.68	32.88	5.08
37033	LIZZANO IN BELVEDERE	937.91	71.13		1009.04	0.00	12.76	0.00
37034	LOIANO	1761.75	351.10	3.64	2116.49	0.08	13.76	0.10
37035	MALALBERGO	3.54	3669.61	31.60	3704.75	10.96	29.77	0.24
37036	MARZABOTTO	776.74	482.73	1.17	1260.63	0.00	14.81	1.69
37037	MEDICINA	9692.43	4072.69	21.99	13787.12	1.82	35.30	1.26
37038	MINERBIO	2.34	3284.06	117.17	3403.58	6.86	31.15	0.78
37039	MOLINELLA	6832.28	3032.52	2.77	9867.57	8.42	22.96	0.45
37040	MONGHIDORO	1020.30	125.85		1146.15	0.00	10.46	0.00
37041	MONTERENZIO	1469.11	257.90	0.97	1727.97	0.69	10.03	3.15
37042	MONTE S.PIETRO	0.50	1987.98	262.41	2250.88	0.73	19.55	2.62
37043	MONTEVEGLIO	1.94	796.98	526.11	1325.02	1.17	32.54	0.64
37044	MONZUNO	1132.21	221.67	1.34	1355.22	0.09	7.73	0.00
37045	MORDANO		744.48	57.24	801.73	4.34	36.80	1.09
37046	OZZANO	2.77	1682.68	2036.08	3721.54	2.86	29.65	2.41
37047	PIANORO	1.48	3163.88	398.06	3563.43	0.20	18.29	4.11
37048	PIEVE DI CENTO		522.76	540.99	1063.75	32.79	29.43	0.00
37049	PORRETTA TERME		514.55	1.86	516.40	0.00	8.21	0.00
37050	SALA BOLOGNESE		3411.83	33.36	3445.19	6.66	40.39	0.39
37051	S.BENEDETTO VAL DI SAMBRIO	731.55	246.55		978.09	0.00	10.27	0.00
37052	S.GIORGIO DI PIANO	1.73	2322.30	119.79	2443.81	12.40	36.29	0.00
37053	S.GIOVANNI IN PERSICET	1.41	9349.75	21.57	9372.73	12.90	33.61	0.27
37054	S.LAZZARO DI SAVENA		174.62	1872.64	2047.26	1.39	29.41	0.00
37055	S.PIETRO IN CASALE	1.44	5473.89	2.68	5478.00	12.18	32.30	1.39
37056	S.AGATA BOLOGNESE	0.19	2919.40	3.64	2923.22	6.98	36.97	1.37
37057	SASSO MARCONI	0.20	1618.56	619.82	2238.58	1.06	24.22	8.09
37058	SAVIGNO	1744.12	417.76	0.51	2162.40	0.01	7.45	0.00
37059	VERGATO	1093.10	369.31		1462.41	0.00	9.41	0.33
37060	ZOLA PREDOSA		658.11	1051.68	1709.80	3.06	40.71	3.19
	Total	54376.75	95981.22	28022.25	178380.22	6.49	28.78	1.17

Municipalities with extended areas with a low allocation risk could host most impacting crops. Some of them, are located in mountainous areas and then it could be possible a yield reduction or even the impossibility to grow maize or wheat. Others are anyway locate in the flat areas, as Crevalcore (with 6512.37 ha of low risk lands and where maize is grown in the 24.76 % of arable lands), Medicina (with 9692.43 ha of low risk lands and where maize is currently grown in only 1.82 % of arable lands).

Using data from the COLT project , which focuses with more details solely on the plain area of the province (table 6.6), 20.96 % of winter crops, in terms of hectares, are located in areas highly vulnerable to maize. Among municipalities, Bazzano, Casalecchio, Dozza, Imola and San Lazzaro presented almost all winter sowable areas in highly vulnerable zones. In table 6.6 it is also possible to identify the proportion of wheat that is grown in each municipality. It ranges from 43.16 % in Bazzano to 71.57 % in Imola (the absolute values in hectares are reported in table 6.7). Again, also with the use of COLT's data, wheat presence in Imola could be optimized in order to minimize the impact.

Again, municipalities as Baricella, Bentivoglio or Crevalcore showed a high percentage (from 93.80% to 71.39 %) of winter crop extension being cultivated in low vulnerable lands (table 6.6). In Crevalcore, in particular, wheat is grown in the 83.77 % of winter crop extensions, suggesting a quite good level of sustainability of wheat allocation for this area. Corresponding hectare values are reported in table 6.7.

Table 6.7 reports hectares of winter sowable lands (EAgc) each municipality and their values in lands with low, moderate and high allocation risk to maize. The comparison of EAgc values from COLT project with values calculated from the 5° ISTAT Census on Agriculture (ISTAT 2000), in the same table also reported, shows that there are for few municipalities some discrepancies. Winter crops values released by COLT project differs from values obtained by summing all single winter crops, and for each municipality, contained in the ISTAT database. The reason could be in the fact that data are not contemporary, COLT refers to 2010 while census to 2000 and annual crop extensions are quite unstable during years. Moreover COLT's data come from the interpretation of remote sensing images, identifying crop and then measuring their extension, while the census is based on statistical survey and questions directly addressed to farmers. Usually extensions resulting from surveys are in general lower respect to image interpretation. The most updated value of single crops available at municipal level refers anyway at 2000, thus comparing winter sowable presence from the two data sources is useful to understand if wheat land portions, that refers to 2000, can be accepted as linkable to COLT data.

Looking at EEee – sowable summer crops (table 6.6), 15.85 % (49340.62 ha) of summer sowable areas in the plains of Bologna (of which 20.84 % cultivated with maize, 9386.83 ha) are grown in areas where maize showed an high allocation risk. These areas are mainly concentrated in the towns of Bazzano, Casalecchio, Dozza, Imola and San Lazzaro. In municipalities where high vulnerable areas are prevalent, maize presence should be reduced. This is the case for example of Bazzano, where even if the whole territory is classified as highly vulnerable, 39,56 % of summer crop extensions are on maize. To be underlined the high variability of maize percentage among municipalities (from less than 1 % to about 58.60 % in Pieve di Cento). Correspondent hectare values are reported in table 6.8, where also a comparison with ISTAT data of 2000 is reported.

The allocation risk map of maize (fig. 6.4) also represents the vulnerability map calculated considering all impacts factors (comprehensive vulnerability map). This map reports thus the highest levels of vulnerability in a certain territory. The allocation risk maps of the other crops are calculated in reference to maize, as this is the most impacting crop, and they can be useful to define their impact compared to maize. For this reason, the levels of impact shown in the maps are necessarily lower than maize. The comparison between the allocation risk maps of different crops can identify whether the crop are somewhat similar in impact and those that have a significantly lower impact and then, for this reason, this last possibly grown in areas where vulnerability is high, or as a substitute of high impacting crops when allocated in areas with high vulnerability.

If the purpose is to compare the site-specific impact of crop presence on the territory, the use of the vulnerability map calculated using all impact factors, which is represented by the allocation risk map of maize, represents the safer situation. For example, if wheat, compared to maize, has a significantly lower allocation risk in the same portion of the territory, maize can have a high impact and wheat classified as low or moderate, but certainly not higher than maize. So if the presence of maize in a certain area is tolerated, it is certainly also that of wheat, but not vice versa.

Table 6.6. Land portion percentage of winter crops (EAgc) and summer crops (EEee) on total sowable (from COLT project) for each municipality of the flat area of the Province and classified based on the impact map of maize. Percentage of maize and wheat in each municipality are from the 5° ISTAT Census on Agriculture.

Municipality	% Eagc - sowable winter crops in vulnerable lands and % of wheat				% EEee - sowable summer crops in vulnerable lands and % of maize			
	low	moderate	high	wheat %	low	moderate	high	maize %
ANZOLA DELL'EMILIA	0.00	80.07	19.93	88.86	0.00	83.66	16.34	18.11
ARGELATO	0.35	71.31	28.33	70.01	0.66	72.94	26.40	17.44
BARICELLA	93.80	6.20	0.00	76.23	94.28	5.72	0.00	23.96
BAZZANO	0.00	0.00	100.00	43.16	0.00	0.00	100.00	39.56
BENTIVOGLIO	74.29	25.70	0.01	72.23	76.83	23.10	0.08	26.13
BOLOGNA	0.00	44.94	55.06	68.48	0.00	41.72	58.28	15.31
BORGO TOSSIGNANO	41.36	46.05	12.59	22.76	26.48	73.52	0.00	5.89
BUDRIO	0.59	92.70	6.71	74.07	0.63	95.09	4.27	14.80
CALDERARA DI RENO	0.00	48.98	51.02	78.83	0.00	44.23	55.77	20.83
CASALECCHIO DI RENO	0.00	0.00	100.00	48.82	0.00	0.00	100.00	0.37
CASALFIUMANESE	0.00	0.82	99.18	51.13	-	-	-	-
CASTEL GUELFO DI BOLOGNA	0.61	89.89	9.50	82.44	0.51	89.63	9.86	6.36
CASTEL MAGGIORE	0.76	28.63	70.61	77.58	0.05	30.05	69.90	20.32
CASTEL SAN PIETRO TERME	14.27	74.26	11.47	58.47	24.40	68.31	7.29	9.84
CASTELLO D'ARGILE	0.00	99.87	0.13	77.98	0.00	99.14	0.86	39.38
CASTELLO DI SERRAVALLE	0.00	73.67	26.33	74.56	0.00	11.64	88.36	1.53
CASTENASO	0.00	57.77	42.23	76.91	0.00	61.86	38.14	10.30
CRESPELLANO	0.00	45.49	54.51	77.65	0.00	43.38	56.62	29.89
CREVALCORE	71.39	28.54	0.07	83.77	76.21	23.79	0.00	43.63
DOZZA	0.00	0.74	99.26	57.33	0.00	0.00	100.00	17.95
GALLIERA	0.00	99.64	0.36	82.25	0.00	99.97	0.03	35.23
GRANAROLO DELL'EMILIA	0.48	70.59	28.94	69.62	1.93	66.78	31.29	14.70
IMOLA	0.00	8.54	91.46	71.57	0.00	9.41	90.59	10.87
MALALBERGO	8.42	90.90	0.68	74.45	9.05	90.20	0.75	23.56
MEDICINA	66.83	30.92	2.25	81.67	68.86	29.30	1.84	5.59
MINERBIO	2.51	93.32	4.17	77.21	2.03	94.97	3.00	16.60
MOLINELLA	64.23	35.54	0.23	69.28	68.08	31.81	0.11	20.44
MONTE SAN PIETRO	0.00	15.91	84.09	54.24	-	-	-	-
MONTEVEGLIO	0.00	32.70	67.30	65.88	0.00	21.34	78.66	12.87
MORDANO	0.00	91.22	8.78	74.32	0.00	89.63	10.37	12.42
OZZANO DELL'EMILIA	0.00	34.23	65.77	71.57	0.03	25.50	74.48	7.65
PIANORO	0.00	58.21	41.79	49.78	-	-	-	-
PIEVE DI CENTO	0.00	65.76	34.24	74.07	0.00	61.72	38.28	58.60
SALA BOLOGNESE	0.00	88.31	11.69	78.26	0.00	91.99	8.01	18.92
SAN GIORGIO DI PIANO	9.52	89.89	0.60	67.72	12.33	85.13	2.55	32.75
SAN GIOVANNI IN PERSICETO	0.00	99.79	0.21	75.47	0.00	99.81	0.19	32.81
SAN LAZZARO DI SAVENA	0.00	3.49	96.51	60.80	0.00	4.37	95.63	5.17
SAN PIETRO IN CASALE	2.71	97.17	0.12	73.64	4.83	95.10	0.07	28.13
SANT'AGATA BOLOGNESE	0.00	99.74	0.26	77.63	0.00	99.85	0.15	18.01
ZOLA PREDOSA	0.00	49.70	50.30	77.03	0.00	35.48	64.52	9.93
Total (%)	**20.55**	**58.49**	**20.96**	**72.74**	**26.25**	**57.90**	**15.85**	**20.84**

Table 6.7. Hectares of winter sowable lands (EAgc) each municipality and their values in lands with low, moderate and high allocation risk to maize. Comparison of EAgc values from COLT project with values calculated from the 5° ISTAT Census on Agriculture.

Municipality	low	moderate	high	EAgc (ha) from COLT project	Eagc (ha) from ISTAT 2000	wheat (ha) from ISTAT2000	wheat %
ANZOLA DELL'EMILIA	-	1033.11	257.16	1290.26	746.08	662.97	88.86
ARGELATO	4.50	908.22	360.87	1273.59	1458.96	1021.37	70.01
BARICELLA	845.77	55.87	-	901.63	1236.48	942.57	76.23
BAZZANO	-	-	295.02	295.02	353.83	152.7	43.16
BENTIVOGLIO	1014.95	351.07	0.14	1366.16	1254.98	906.41	72.23
BOLOGNA	-	532.01	651.93	1183.94	2143.81	1468.1	68.48
BORGO TOSSIGNANO	9.13	10.17	2.78	22.08	154.96	35.27	22.76
BUDRIO	22.25	3470.69	251.09	3744.03	4040.79	2992.88	74.07
CALDERARA DI RENO	-	526.66	548.69	1075.35	1204.93	949.79	78.83
CASALECCHIO DI RENO	-	-	12.06	12.06	167	81.53	48.82
CASALFIUMANESE	-	0.19	23.37	23.56	588.95	301.11	51.13
CASTEL GUELFO DI BOLOGNA	4.83	715.55	75.65	796.02	957.48	789.35	82.44
CASTEL MAGGIORE	5.91	222.90	549.74	778.54	887.8	688.76	77.58
CASTEL SAN PIETRO TERME	424.31	2207.68	341.04	2973.03	2908.58	1700.77	58.47
CASTELLO D'ARGILE	-	793.75	1.06	794.81	980.98	764.96	77.98
CASTELLO DI SERRAVALLE	-	2.05	0.73	2.78	300.43	224.01	74.56
CASTENASO	-	571.43	417.67	989.10	1188.03	913.74	76.91
CRESPELLANO	-	466.97	559.46	1026.43	960.44	745.78	77.65
CREVALCORE	2206.28	882.05	2.16	3090.49	2111.34	1768.73	83.77
DOZZA	-	3.58	480.34	483.91	530.14	303.95	57.33
GALLIERA	-	1031.96	3.74	1035.69	666.82	548.45	82.25
GRANAROLO DELL'EMILIA	5.38	796.73	326.63	1128.74	1151.2	801.52	69.62
IMOLA	-	292.30	3130.95	3423.25	3572.54	2556.7	71.57
MALALBERGO	102.72	1108.64	8.32	1219.68	919.03	684.2	74.45
MEDICINA	3972.37	1837.69	133.56	5943.61	5140.74	4198.27	81.67
MINERBIO	46.97	1745.18	77.89	1870.04	1041.6	804.18	77.21
MOLINELLA	1862.75	1030.71	6.80	2900.25	2819.23	1953.27	69.28
MONTE SAN PIETRO	-	2.23	11.77	14.00	406.61	220.55	54.24
MONTEVEGLIO	-	16.41	33.77	50.17	488.08	321.54	65.88
MORDANO	-	353.05	33.97	387.02	367.67	273.27	74.32
OZZANO DELL'EMILIA	-	284.30	546.14	830.43	1278.03	914.65	71.57
PIANORO	-	2.75	1.98	4.73	1144.81	569.94	49.78
PIEVE DI CENTO	-	306.03	159.35	465.38	408.87	302.87	74.07
SALA BOLOGNESE	-	1660.36	219.81	1880.17	1408.39	1102.19	78.26
SAN GIORGIO DI PIANO	68.84	650.29	4.33	723.45	975.43	660.55	67.72
SAN GIOVANNI IN PERSICETO	-	3072.75	6.55	3079.30	3722.66	2809.4	75.47
SAN LAZZARO DI SAVENA	-	37.73	1044.86	1082.59	800.31	486.58	60.80
SAN PIETRO IN CASALE	59.86	2147.52	2.67	2210.04	2562.99	1887.44	73.64
SANT'AGATA BOLOGNESE	-	918.60	2.38	920.98	1081.57	839.66	77.63
ZOLA PREDOSA	-	277.50	280.90	558.40	655.08	504.61	77.03
EAgc Totale	**10656.79**	**30326.66**	**10867.27**	**51850.71**	**54787.65**	**39854.59**	**72.74**

Table 6.8. Hectares of summer sowable lands (EEee) each municipality and their values in lands with low, moderate and high allocation risk to maize. Comparison of EEgc values from COLT project with values calculated from the 5° ISTAT Census on Agriculture.

Municipality	low	moderate	high	EEee (ha) from COLT project	EEee (ha) from ISTAT 2000	maize (ha) from ISTAT 2000	maize %
ANZOLA DELL'EMILIA	-	886.03	173.11	1059.14	657.49	119.09	18.11
ARGELATO	7.64	849.90	307.60	1165.14	934.54	163.03	17.44
BARICELLA	1134.69	68.88	-	1203.58	1295.77	310.51	23.96
BAZZANO	-	-	163.46	163.46	113.94	45.07	39.56
BENTIVOGLIO	831.09	249.88	0.82	1081.79	1024.33	267.7	26.13
BOLOGNA		358.46	500.73	859.19	1368.02	209.39	15.31
BORGO TOSSIGNANO	-	3.88	-	5.28	102.33	6.03	5.89
BUDRIO	23.66	3545.10	159.31	3728.08	3719.08	550.57	14.80
CALDERARA DI RENO	-	400.01	504.43	904.44	1017.09	211.88	20.83
CASALECCHIO DI RENO	-	-	4.21	4.21	54.72	0.2	0.37
CASTEL GUELFO DI BOLOGNA	4.43	771.96	84.90	861.28	915.57	58.26	6.36
CASTEL MAGGIORE	0.39	223.14	519.07	742.60	688.54	139.93	20.32
CASTEL SAN PIETRO TERME	343.84	962.37	102.72	1408.93	1816.52	178.7	9.84
CASTELLO D'ARGILE	-	721.10	6.23	727.33	998.11	393.1	39.38
CASTELLO DI SERRAVALLE	-	0.24	1.81	2.04	116.03	1.77	1.53
CASTENASO	-	470.59	290.15	760.74	814.11	83.86	10.30
CRESPELLANO	-	262.25	342.27	604.52	860.36	257.2	29.89
CREVALCORE	3311.20	1033.77	0.07	4345.05	3299.38	1439.4	43.63
DOZZA	-	-	176.90	176.90	222.88	40	17.95
GALLIERA	-	1528.84	0.41	1529.25	670.84	236.37	35.23
GRANAROLO DELL'EMILIA	20.54	711.21	333.23	1064.98	957.96	140.79	14.70
IMOLA	-	275.97	2655.82	2931.79	2632.18	286.08	10.87
MALALBERGO	136.76	1362.44	11.29	1510.49	1068.81	251.78	23.56
MEDICINA	3430.91	1459.96	91.89	4982.75	3872.21	216.61	5.59
MINERBIO	31.69	1480.84	46.74	1559.27	1066.49	177.08	16.60
MOLINELLA	3471.30	1622.07	5.52	5098.88	3505.79	716.64	20.44
MONTEVEGLIO	-	4.47	16.48	20.95	90.16	11.6	12.87
MORDANO	-	256.40	29.66	286.06	259.24	32.19	12.42
OZZANO DELL'EMILIA	0.17	160.19	467.93	628.29	1152.76	88.24	7.65
PIEVE DI CENTO	-	350.69	217.46	568.15	575.79	337.41	58.60
SALA BOLOGNESE	-	1490.73	129.81	1620.53	960.33	181.73	18.92
SAN GIORGIO DI PIANO	77.25	533.49	15.97	626.71	689.52	225.79	32.75
SAN GIOVANNI IN PERSICETO	-	3145.48	6.04	3151.52	3285.34	1077.87	32.81
SAN LAZZARO DI SAVENA	-	13.50	295.56	309.06	444.96	22.99	5.17
SAN PIETRO IN CASALE	123.77	2436.77	1.78	2562.32	2529.36	711.49	28.13
SANT'AGATA BOLOGNESE	-	842.59	1.24	843.83	880.25	158.52	18.01
ZOLA PREDOSA	-	85.90	156.20	242.11	382.23	37.96	9.93
EEee Totale	**12950.72**	**28569.10**	**7820.80**	**49340.62**	**45043.03**	**9386.83**	**20.84**

Guideline for developments of new policy for crop chains introduction in rural areas. Crop yield or environmental impacts ?

LCA-GIS approach takes into account the crop production chain effects on environment, through the integration of a well known and wide recognized tool as LCA with the potentials of GIS in studying the landscape. The environmental benefit will be as high as possible as much LCA impact indicators are used. This approach thus gives the possibility to include in the land suitability studies, mainly focused on maximizing crop yields, also the relation of the environmental impact of the crop production chain with site-specific vulnerability characteristics. This bidirectional approach highlights a crucial aspect in land suitability studies of crops (food and no food): crop allocation may be different basing on which aspect is considered as more important (yield or impact).

The model in fact returns hypothesis on the optimal land use in order to minimize the environmental impact, that it could also be not potentially the best choice from the economic point of view. Yield is directly linked to income. This study do not take in account the incomes from different crops, which, things being equal, will be definitely the main determinant in driving the land allocation by farmers. The product prize defined by the market or by economic trends also defines indirectly the extension of crops for a given area, as it may drive farmers decision on growing a crop instead than another. It is also true that social perception of the environmental problem is more and more important in the modern society, thus one can expect that also benefits coming from a sustainable choices in land uses will become an important determinant in management decisions or even be related to an economic value. Basing on which aspect (yield or impact), crop preference for a given location may be different.

In fig. 6.13 it is schematically represented how environmental impact of a crop and the yield could be linked.

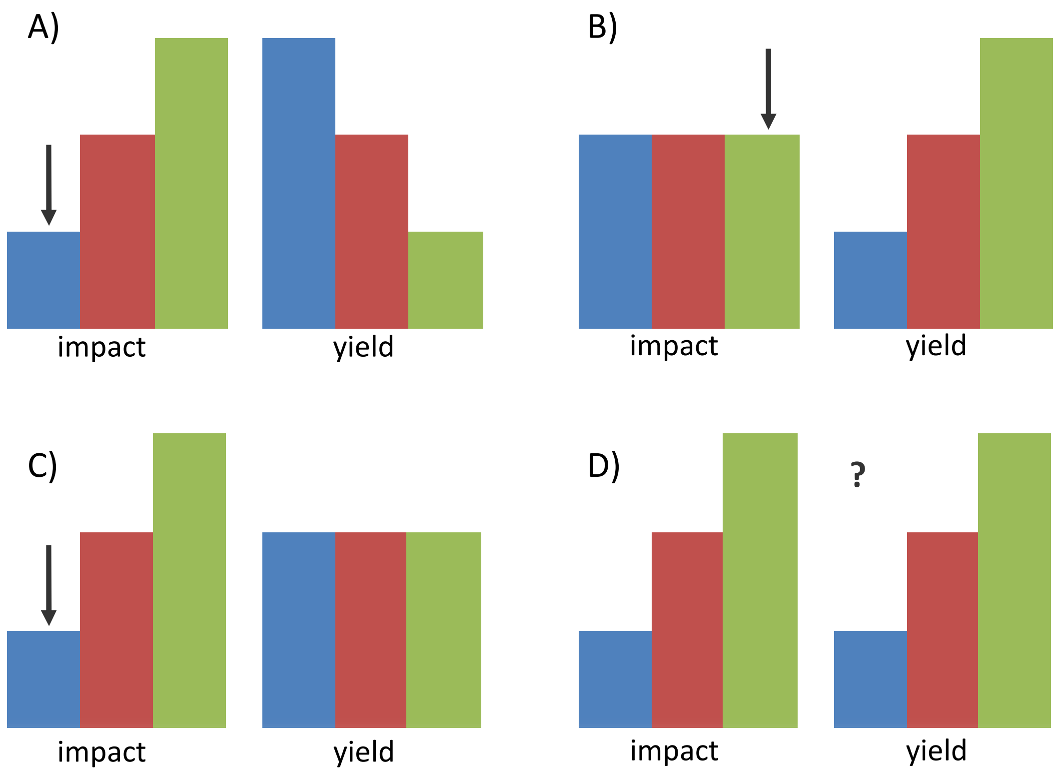


Figure 6.13. Possible relationships between environmental impact and yield. Each colour represent a different crop. Arrow indicates best crop option.

In the cases A, B and C, the choice about with crop it could be preferred is immediate. In the case A, lowest impacting crop also produces more yield, this choice is sustainable under the environmental and economic point of view. In B, impact is similar for all crops, thus the crop with the highest yield could be preferred. In the case C, yields are similar, the crop with the lowest impact may be preferred. More complicated is the scenario of case D, where impacts and yields increment both increases. In this case, a high impacting crop could be preferred justified by his higher yield level, or, vice versa, a lower impacting crop could be preferred in order to protect the environment, but providing a lower yield. Another variable is represented by the spatial variability of site-specific conditions, e.g. in term of fertility or more in general in of pedo-climatic suitability, that could affect yields. To solve the problem it is necessary to model these relations in order to understand for example the acceptable level of environmental risk to justify high yield levels. Assessment of marginal increments of impact and yield in order to compare them, maybe giving an economic value to these marginal increment, it could be necessary. Other option is to attribute a cost to the environmental damage of a crop production chain. Ones they are known, a potential environmental risk could be supported since the marginal cost will be lower that the marginal income deriving from the yield (fig. 6.14).

Impact depends by input intensification in the agronomic management, thus increasing the environmental cost (fig. 6.14). At the same time, the input intensification may increase yields following trends that could be different among crops (fig. 6.14). Ones defined the intensification level corresponding to a maximum acceptance of the impact (fig. 6.14), crop “B” in fig. 6.14 may be preferred in the case of lower agronomic inputs (e.g. nitrogen fertilization) or crop A in the case of higher input intensification.

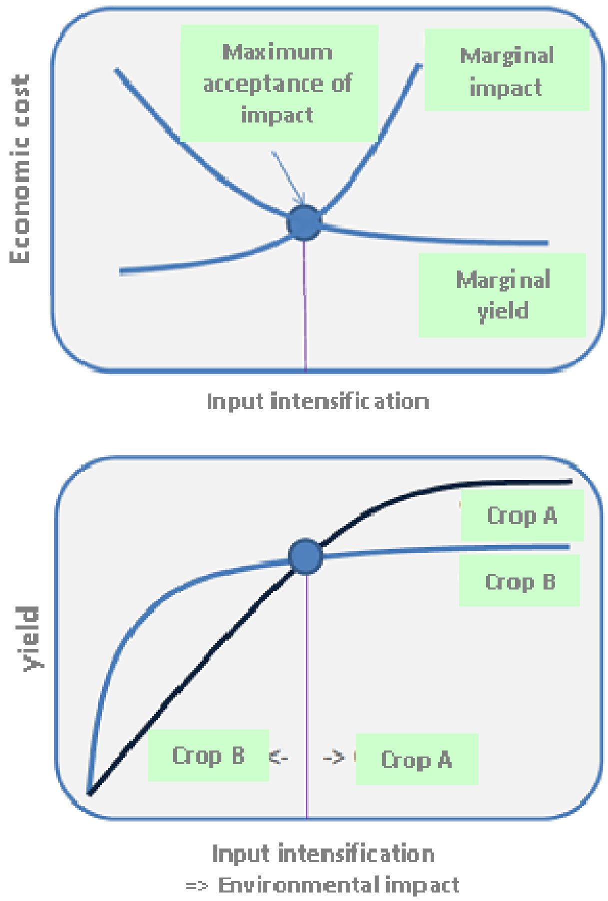


Figure 6.14. Importance of the agronomic input on crop preference. Crop "A" has a more correlated answer to input intensification respect to crop B, which early reaches a platform. Crop "B" has lower yield at high input levels, but more efficient at low inputs. If maximum acceptable environmental risk corresponds to input levels that fall at left of the two crop curves intersection, crop B can be preferred, and vice versa.

Definitely, the identification of the most suitable crop from the environmental point of view is linked to the applied agronomic practice; the use of different practices could bring to different choices.

More over, in particular when dealing with energy crop as a possible alternative land use for minimizing environmental impacts, one big issue is the food – no food competition. Some studies limit the analysis of land suitability for energy crops to marginal lands, in order to minimize current agriculture changes in practices and cash crops production, and thus do not deal with socio political problems, e.g. food – no food crop competition. Not necessarily this assumption ensures the best choice from the environmental point of view. Reasonably, food and feed crops will be prioritizing on energy crops, thus they should be subjected to a minimum size based on the needs of the society. Moreover, food crop cultivation should maintain a sustainable income, thus they also have to reach a sustainable yield. Moving high impacting food crops (e.g. maize) to lower vulnerable but less suitable lands will produce environmental benefits, but also a lower income. This last could be again supported by fiscal tools justified by the environmental benefits. Nonetheless a decision maker could decide to support the cultivation of maize in less vulnerable soils if the environmental benefits will entail economic returns for farmers. E.g. an important food crop such as maize, once defined pedoclimatic constraints, could be moved from more fertile lands to lower and less vulnerable ones.

Commensurate environmental benefit to decrease production by placing incentives to support high impacting crop productions in less vulnerable soils, or even better, to support soil-crop combinations with minor environmental risks, would be a modern concept of agriculture, this last no longer seen as an agricultural system but as an agro-environmental system.

The integration of the bidirectional approach with economical and land use management model is essential to answer to above aspects.

Economical models may be integrated at the beginning of a land allocation procedure to define relative food – no food hectares for crops. However, once the environmental benefits will be opportunely monetized, also in terms of subsidies, economic returns for farmers associated to crop-specific environmental benefits should also be taken in consideration. This aspect may justify new crops allocation rules, as:

high impacting and high value crops in less vulnerable but low fertile lands; low impacting ligno-cellulosic crops in high vulnerable and fertile lands.

Integrated model defining economic variable as production pricing, incomes, market trends, etc. linked to crop allocation scenarios and political choices (e.g. protected areas, Nitrate Directive, cultivation rules, ect.) will represent a Decision Support System to be applied under a sustainable planning strategy, able to understand the best land use in order to maximize a broad sustainability concept: implement decisions to be more rational and effective in reducing emissions, help in solving some delicate issues such as food - bioenergy competition, maximizing at the same time the cost-effectiveness and environmental benefits.

Decision Support Systems based on Open-sources GIS

In particular when considering models and novel approaches to be part of a Decision Support System (DSS), the cost aspect of these tools sometimes is the main determinant in particular if they should be used by public offices or institutions.

Currently a wide range of software for the management of spatial information, developed by private or public institutions such as universities and research centers, are available. Often consist of software packages specialized in dealing with various aspects of spatial data. They can be commercial software, whose code is copyrighted, or "open source", when the source code is freely distributed. These last are of a particular importance to be applied when building DSS tool because of their inexpensiveness. Open sources geo – spatial tools have been developed by several research institutions. Many references are now available in the web or in specialized journals (fig. 6.15).

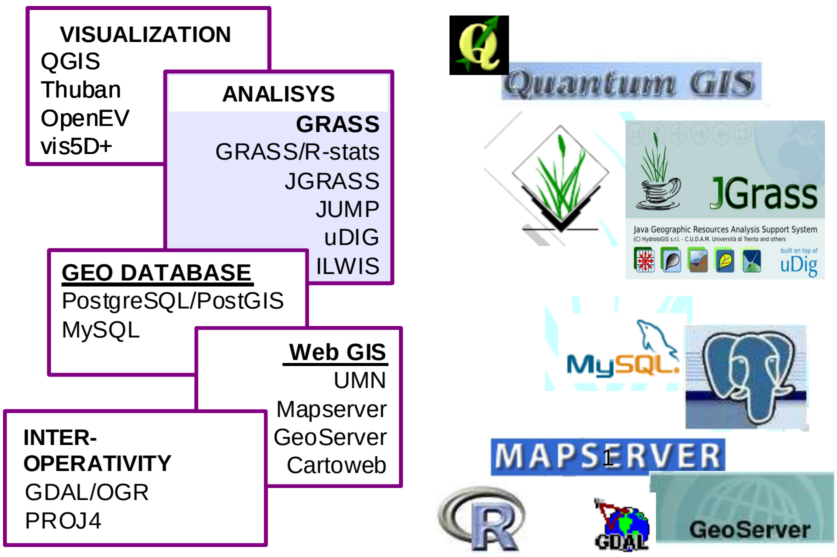


Figure 6.15. Most common Open Sources systems for land studies.

In the last years they became certainly ready to accomplish each kind of geo-spatial task.

Advantages are not only linked to inexpensiveness. The use of this type of application opens up new possibilities for development, implementation and "customization" in regional studies with many different purposes, because the source code is liberally available. The advantages are summarized in the great freedom for users and developers, free implementation, ability to modify and redistribute the code, compatibility with libraries of free and private data formats, standards compliance of the Open Geospatial Consortium (OGC) for the sharing and use of the Web Map Service (WMS) and Web Feature Service (WFS), drastic reduction in costs. Specific skills are of course required to work with these tools, as sometimes they could not be user-friendly as commercials are.

More details may be found in the Open Geospatial Consortium (OGC) website (www.opengeospatial.org/) or at the Geospatial free and open Source Software community website (www.gfoss.it/drupal/).

7. Main conclusions

Main conclusions from the method use

Main conclusions from the method use

This study addressed the crop impact in the assessment of land use and the relation with energy crops. LCA-GIS approach gave the possibility to include the environmental impact in land suitability studies, taking into account the mutual effects between environment and crops, practically defining a bidirectional approach. LCA, a well known and standard tool, it was recognized to be valuable in identifying impact indicators with local effect to be related with site specific environmental vulnerability, this last resulting from a land analysis carried out with the support of GIS. Vulnerability maps to the involved LCA impacts represented the link of impacts with site-specific condition and the calculation of an "allocation risk" for each crop-vulnerable land combination gave the possibility to identify the best crop for each location.

The LCA-GIS tool revealed that the optimal crop allocation able to minimize the environmental impact can be different basing on which impact indicator is considered. If eutrophication risk is a priority, arundo, miscanthus and switchgrass could be grown in all lands, while maize, rapeseed, wheat, sunflower and fiber sorghum could be grown only in identified lower vulnerable areas.

In general perennial grasses, as miscanthus and switchgrass, can be cultivated in highly vulnerable lands with an allocation risk that was classified as low respect to maize. This aspect is even more evident when multiple impact indicators are considered, for which only switchgrass can be cultivated in high vulnerability lands. In fact, in some cases, e.g. in the case of eutrophication, giant reed and miscanthus were also allowed. In moderate vulnerability area, sunflower and wheat were allowed in the case of FWT, while when considering all impact indicators, they can be cultivated only in low vulnerable areas. More in detail, taking into account 3 impacts (eutrophication, human toxicity and freshwater toxicity) managed with the CMM, 16.24 % (60083 ha) of the province showed an allocation risk classified as high if maize will be there allocated, and 0.58 % (2128 ha) in the case of f sorghum. Maize presented a high allocation risk in the central part of the province, corresponding mainly to areas classified as vulnerable to nitrate by the Water Protection Plan and also as the most densely populated. F sorghum showed a risk classified as high in only a few strips, where the vulnerability to eutrophication is high and where are located main areas for the protection of groundwater and aquifers. Rapeseed, wheat and sunflower showed an impact classified as medium in the central area of the territory, while switchgrass did not show significant impacts throughout the province, respect to maize and other crops. Cynara, miscanthus and giant reed showed a low impact, except for the most vulnerable areas from the point of view of the protection of water, where these three crops showed an impact classified as medium. In this view, perennial grasses represent and alternative land use to consider for high vulnerable lands when building up planning strategies for increasing the sustainability level of the land use in rural areas. Perennial grasses can also be considered as not competing for agricultural land because they can be grown on marginal or degraded lands where intensive agricultural practices harm the environment (e.g.

promoting soil erosion), and where the economic returns for farmers is not sustainable.

LCA-GIS tool gave the possibility to release maps of optimal land allocation that overlaid with municipalities, or linked with the current land use, can indicate if most impacting crop production chains are grown in high vulnerable lands, and thus advising on how to change land uses in order to optimize environmental benefits. For example in the flat fertile area of the province of Bologna, 10867.27 ha of arable winter crops (including wheat) are grown in areas classified as highly vulnerable. The analysis also showed that 7820.80 ha of summer crops (which includes maize) are grown in areas classified as highly vulnerable. The municipality of Imola for example reported the highest number of hectares of sowable land in high-risk areas (8054.45 ha). Wheat is present in the 32.88 % of Imola's sowable lands, and as his impact could be compared to maize when considering multiple impact indicators, it could be effectively thought to partially substitute it with lower impacting crop in order to minimize environmental impacts. Looking at summer crops, 49340.62 ha of summer sowable areas in the plains of Bologna (of which 20.84 % cultivated with maize, 9386.83 ha) are grown in areas where maize showed an high allocation risk. This land portion can be substituted with some grasses to increase sustainability.

The use of multiple impact indicators with local effect increases the environmental sustainability of crop allocation, but also can introduces uncertainty in giving weighting factors or when classifying vulnerability scores in calculating total impact indexes or total vulnerability maps. This is avoided with the use of the composed multiplicative method (CMM). The CMM well suits the possibility to use more than two impact categories. Subjectivity and the issue of the classification method choice still remain important components of the method. The definition of a standard methodology to provide consistent vulnerability maps for all impact categories as defined in the LCA, and also for their integration, is required. Vulnerability has to be as much as possible related to measurable, not subjective and broadly available land information, thus to allow the reproducibility of the analysis. The characterization factor is the first step within LCA procedure where it may be possible to act in order to “adjust” the impact level to the site-specific vulnerability. Impact indicators will be no more a single value for each crop, but a range of values showed in a map, thus defining a geo-LCA tool. This procedure, although desirable, requires deep knowledge on impact definitions and about the inner running operations of LCA procedures, that of course can be the subject for further studies.

The LCA-GIS method here proposed wanted to use the standard LCA procedure, and thus postponing the integration with land site-specific characteristics at the end of the LCA procedure. In this way, potentially, all impact indicators available in the bibliography may be used, thus giving the possibility to use research recourses to understand the impact for a huge number of crop or agro-production chains.

The bidirectional approach, i.e. considering the mutual effect between crop and environment, highlights a crucial issue in land suitability studies of crops (food and no food): crop allocation may be different basing on which aspect is considered as more important (yield or impact). As a general rule, ideally, the crop with the highest impact should be grown on less vulnerable areas, and vice versa, crop with a low impact (as energy grasses), should be grown in high vulnerable areas. This not necessary is also the best option also from the yield (or farmer's income) point of view. For example in this study an important portion of high vulnerable lands were also the most fertile ones. In some cases it can be accepted to reserve areas of greatest fertility but with height vulnerability usually hosting important cash crops as maize or wheat, to perennial ligno-cellulosic crops as switchgrass, justified by their most significant environmental sustainability. Currently, there are lot of political and economic constraints which hinders this principle, e.g. food – no food competition, agronomic limitations linked to the mechanization, social constraints as the difficulty on accepting a novel and perennial crop, etc., and of course this principle is more ease to implement in a developing area respect to regions with a well established agricultural structure. However, in a context in which sustainability is recognized and driven by fiscal policy, this principle may also assume and economic value linked to its environmental benefit, and then being a balance for eventually lower yields.

Commensurate environmental benefits to decreased production by placing incentives to support high impacting crop productions in less vulnerable soils, or even better, to support soil-crop combinations with minor environmental risks, would be a modern concept of agriculture, finally seen as an agro-environmental system.

Modern Decision Supporting Systems should include as many as possible criteria, incorporating all possible land characteristics and socio-economic factors, coupled with the impact or benefit for the environment of crops production chains. I this way reliable maps will be produced, more than increasing the complexity of tools and methods.

References

Baux, A., N. Colbach, et al. (2011). "Crop management for optimal low-linolenic rapeseed oil production-Field experiments and modelling." European Journal of Agronomy 35(3): 144-153.

Biewinga, E. E. and G. Van der Bijl (1996). Sustainability of Energy Crops in Europe. Utrecht, CLM 234 -1996.

Brentrup, F. (2003). "Life cycle assessment to evaluate the environmental impact of arable crop production." International Journal of Life Cycle Assessment 8(3): 156-156.

Brentrup, F., J. Küsters, et al. (2000). "Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector." The International Journal of Life Cycle Assessment 5(6): 349-357.

Brentrup, F., J. Kusters, et al. (2001). "Application of the Life Cycle Assessment methodology to agricultural production: an example of sugar beet production with different forms of nitrogen fertilisers." European Journal of Agronomy 14(3): 221-233.

Brentrup, F., J. Kusters, et al. (2002). "Life Cycle Impact assessment of land use based on the Hemeroby concept." International Journal of Life Cycle Assessment 7(6): 339-348.

Brentrup, F., J. Kusters, et al. (2004). "Environmental impact assessment of agricultural production systems using the life cycle assessment methodology - I. Theoretical concept of a LCA method tailored to crop production." European Journal of Agronomy 20(3): 247-264.

Brentrup, F., J. Kusters, et al. (2004). "Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology - II. The application to N fertilizer use in winter wheat production systems." European Journal of Agronomy 20(3): 265-279.

Burrough, P. A. and R. A. McDonnell (1998). Principles of geographical information systems. Oxford, Oxford University Press.

Caldiz, D. O., F. J. Gaspari, et al. (2001). "Agro-ecological zoning and potential yield of single or double cropping of potato in Argentina." Agricultural and Forest Meteorology 109(4): 311-320.

Carpenter, G., A. N. Gillison, et al. (1993). "DOMAIN - A FLEXIBLE MODELING PROCEDURE FOR MAPPING POTENTIAL DISTRIBUTIONS OF PLANTS AND ANIMALS." Biodiversity and Conservation 2(6): 667-680.

Communities, C. o. t. E. (1999). Directions towards sustainable agriculture. COM (1999) 22 final. Brussels.

Consoli, F., D. Allen, et al. (1993). Guidelines for life-cycle assessment: A “Code of Practice”. Brussels, Society of Environmental Toxicology and Chemistry (SETAC).

Cosentino, S. L., C. Patane, et al. (2007). "Effects of soil water content and nitrogen supply on the productivity of Miscanthus x giganteus Greef et Deu. in a Mediterranean environment." Industrial Crops and Products 25(1): 75-88.

Cosentino, S. L., V. Copani, et al. (2006). "First results on evaluation of Arundo donax L. clones collected in Southern Italy." Industrial Crops and Products 23(2): 212-222.

COTIR-ARSSA (2008). Indagine Territoriale Della Vocazionalità Del Territorio Per L’introduzione Di Colture Bioenergetiche.

Dalla Marta, A., M. Mancini, et al. (2010). "Energy crops for biofuel production: Analysis of the potential in Tuscany." Biomass & Bioenergy 34(7): 1041-1052.

Di Virgilio, N., S. Fazio, et al. (2010). A new methodological study to allocate energy crops at different scale levels: a multidirectional approach. 18th European Biomass Conference and Exhibition, Lyon Convention Centre - Cité Internationale - France.

Dumanski, J., R. Peiretti, et al. (2006). The paradigm of conservation agriculture. World Association of Soil and Water Conservation.

ECOCROP2004 (2005). "1) The crop environmental requirements database. 2) The crop environmental response database."

El Bassam, N. (1998a). "C3 and C4 plant species as energy sources and their potential impact on environment and climate." Renewable Energy 15(1-4): 205-210.

El Bassam, N. (1998b). Energy plant species, James and James (Science publishers) Ltd.

EPS , E. P. S. (2009). "Plan for Protection of Waters." from www.provincia.bologna.it/ambiente/Engine/RAServePG.php/P/285111030202.

ERMESAmbiente. (2005). "Piano di tutela delle acque - Del. Assemblea Legislativa n. 40/2005." from http://serviziambiente.regione.emilia-romagna.it/PTA/servlet/AdapterHTTP?ACTION_NAME=SCARICA_CARTOGRAFIA_ACTION.

FAO. "ECOPORT 2006: Ecological knowledge management system." from http://ecoport.org/.

Fiorese, G. and G. Guariso (2010). "A GIS-based approach to evaluate biomass potential from energy crops at regional scale." Environmental Modelling & Software 25(6): 702-711.

Gericke, D., L. Bornemann, et al. (2012). "Modelling Ammonia Losses After Field Application of Biogas Slurry in Energy Crop Rotations." Water Air and Soil Pollution 223(1): 29-47.

Heywood, I., S. Cornelius, et al. (2006). An introduction to Geographical Information Systems, Pearson Education Limited.

Hodsman, L., M. Smallwood, et al. (2005). The promotion of non-food crops, National Non-Food Crops Centre.

ISO (2000). Environmental management—life cycle assessment—life cycle impact assessment. International Standard ISO 14042:2000. Geneva.

ISTAT. (2000). "5° Censimento generale dell'Agricoltura. Caratteristiche strutturali delle aziende agricole." From

http://www.census.istat.it/index_agricoltura.htm.

Kalogirou, S. (2002). "Expert systems and GIS: an application of land suitability evaluation." Computers, Environment and Urban Systems 26(2-3): 13.

Kasprzak, T. (1992). Multicriterial Decision Support Systems. Warsaw, Warsaw University Publisher.

Krasuska, E., C. Cadorniga, et al. (2010). "Potential land availability for energy crops production in Europe." Biofuels Bioproducts & Biorefining-Biofpr 4(6): 658-673.

Krupa, T. and G. Kunikowsky (2006). Morphology analysis in land suitability assessment. 26th Annual ESRI International User Conference, August 7–11, 2006. San Diego: 11.

Lake, I. R., A. A. Lovett, et al. (2003). "Evaluating factors influencing groundwater vulnerability to nitrate pollution: developing the potential of GIS." Journal of Environmental Management 68(3): 315-328.

Lastrico, A., S. Arnone, et al. (1990). "SPECIES (SURVEY OF PLANTS EXPLOITABLE AS CROPS FOR INDUSTRY AND ENERGY SUPPLIES) DATA-BASE." Biomass for Energy and Industry, Vols 1 and 2: Policy, Environment, Production and Harvesting / Conversion and Utilisation of Biomass: A507-A511.

Lewandowski, I. and A. Heinz (2003). "Delayed harvest of miscanthus - influences on biomass quantity and quality and environmental impacts of energy production." European Journal of Agronomy 19(1): 45-63.

Lindeijer, E. (1996). Normalization and evaluation. Towards a methodology for life cycle impact assessment. H. A. Udo de Haes. Brussels, SETAC.

Lord, R., J. Atkinson, et al. (2008). "BIOMASS, REMEDIATION, RE-GENERATION (BioReGen LIFE PROJECT): RE-USING BROWNFIELD SITES FOR RENEWABLE ENERGY CROPS." Consoil 2008: Theme E - Remediation Concepts & Technologies, Vols 1-3: 630-639.

Marletto, V., F. Zinoni, et al. (1993). "CRITERIA - AN INTEGRATED GEOGRAPHICAL SYSTEM FOR SOIL-WATER MONITORING." Ix Simposium Pesticide Chemistry: Mobility and Degradation of Xenobiotics: 695-706.

McLaughlin, S. B. and M. E. Walsh (1998). "Evaluating environmental consequences of producing herbaceous crops for bioenergy." Biomass & Bioenergy 14(4): 317-324.

Monti, A. and A. Zatta (2009). "Root distribution and soil moisture retrieval in perennial and annual energy crops in Northern Italy." Agriculture Ecosystems & Environment 132(3-4): 252-259.

Monti, A., P. Venturi, et al. (2001). "Evaluation of the establishment of lowland and upland switchgrass (Panicum virgatum L.) varieties under different tillage and seedbed conditions in northern Italy." Soil & Tillage Research 63(1-2): 75-83.

Monti, A., S. Fazio, et al. (2009). "Cradle-to-farm gate life cycle assessment in perennial energy crops." European Journal of Agronomy 31(2): 77-84.

Nielsen, K. H. (1994). "ENVIRONMENTAL ASPECTS OF USING WASTE-WATERS AND SLUDGES IN ENERGY FOREST CULTIVATION." Biomass & Bioenergy 6(1-2): 123-132.

RER, S. (2011). "6° Censimento dell'agricoltura 2010." 2011. from http://www.regione.emilia-romagna.it/wcm/statistica/censimenti/censimenti/censagri_2010.htm.

Rozakis, S., S. Casalegno, et al. (2001). "Multiple criteria decision-making for bio-energy projects assisted by GIS: current applications and perspectives." Options méditerranéennes 48: 17.

Sàez, R. M., M. Varela, et al. (2000). A multiple criteria decision tool for the integration of energy crops into the Southern Europe energy system. 1st World Conference on Biomass for Energy and Industry, 5-9 June 2000., Sevilla, Spain.

Samson, R., S. Mani, et al. (2005). "The potential of C4 perennial grasses for developing a global bio-heat industry." Criti. Rev. Plant Sci(24): 461-495.

Semere, T. and F. M. Slater (2007). "Ground flora, small mammal and bird species diversity in miscanthus (Miscanthus x giganteus) and reed canary-grass (Phalaris arundinacea) fields." Biomass & Bioenergy 31(1): 20-29.

Severi, P. and L. Bonzi (2008). Approfondimento delle “Zone di Protezione delle acque sotterranee:aree di ricarica” nel territorio di pedecollina-pianura della Provincia di Bologna. Relazione tecnica a corredo della cartografia prodotta, Servizio Geologico, Sismico e dei Suoli.

Severi, P., F. Berrè, et al. (2002). Nuova Carta Regionale della Vulnerabilità: Aspetti Metodologici. Determinazione n. 6636 del 6/7/2001. D. A. e. d. d. s. e. d. costa. Bologna, Regione Emilia Romagna.

Sims, R. E. H., A. Hastings, et al. (2006). "Energy crops: current status and future prospects." Global Change Biology 12(11): 2054-2076.

Smith, J. U., P. Smith, et al. (2004). "How nitrate vulnerable zones can reduce the adverse environmental impact of productive arable agriculture." Controlling Nitrogen Flows and Losses: 85-87.

Spisni, A. and M. C. Mariani (2010). RELAZIONE COLT2010: PARTE TELERILEVAMENTO, ARPA Emilia-Romagna.

Standardization, I. o. (1997). Life Cycle Assessment-principles and framework. ISO 14040-43.

StatisticaE-R. "Statistics of the Emilia-Romagna region." from http://statistica.regione.emilia-romagna.it/.

Tilman, D., J. Hill, et al. (2006). "Carbon-negative biofuels from low-input high-diversity grassland biomass." Science 314(5805): 1598-1600.

Tuck, G., M. J. Glendining, et al. (2006). "The potential distribution of bioenergy crops in Europe under present and future climate." Biomass & Bioenergy 30(3): 183-197.

Udo De Haes, H. A., O. Jolliet, et al. (1999a). "Best available practice regarding impact categories and category indicators in life cycle impact assessment. Part I." International Journal of LCA(4): 9.

Velthof, G. L., D. Oudendag, et al. (2009). "Integrated Assessment of Nitrogen Losses from Agriculture in EU-27 using MITERRA-EUROPE." Journal of Environmental Quality 38(2): 402-417.

Wang, W., K. J. Davis, et al. (2006). "An approximate footprint model for flux measurements in the convective boundary layer." Journal of Atmospheric and Oceanic Technology 23(10): 1384-1394.

Yin, X., H. Ma, et al. (2012). "Comparison of four different enhancing methods for preparing biodiesel through transesterification of sunflower oil." Applied Energy 91(1): 320-325.

Zegada-Lizarazu, W. and A. Monti (2011). "Energy crops in rotation. A review." Biomass & Bioenergy 35(1): 12-25.

Zegada-Lizarazu, W., H. W. Elbersen, et al. (2010). "Agronomic aspects of future energy crops in Europe." Biofuels Bioproducts & Biorefining-Biofpr 4(6): 674-691.

Published papers directly connected with the thesis

Di Virgilio N., Fazio S., Battistel E., Monti A. 2011. Advances in Bi-Directional Method for Land Allocation of Energy Crops. EU BC&E Conference Proceedings 2011. pp. 2393. ISBN-10: 8889407557. ISBN-13: 978-8889407554. Oral presentation.

Di Virgilio N., Fazio S., Fernando A., Monti A., 2010. A new methodological study to allocate energy crops at different scale levels: a multidirectional approach. 18th European Biomass Conference and Exhibition, 3 - 6 May 2010, Lyon Convention Centre - Cité Internationale - France. ISBN: 978-88-89407-56-5. DOI: 10.5071/18thEUBCE2010-OE1.2. Oral presentation.

Fernando, A.L., Duarte, M.P., Almeida, J., Boléo, S., Di Virgilio, N., Mendes, B., 2010. The Influence of Crop Management in the Environmental Impact of Energy Crops Production. 18th European Biomass Conference and Exhibition, 3 - 6 May 2010, Lyon Convention Centre - Cité Internationale - France. ISBN: 978-88-89407-56-5. DOI: 10.5071/18thEUBCE2010-VP5.3.6. Visual presentation.

Fernando A., Duarte M.P., Di Virgilio N., Mendes B. 2009. Is miscanthus a sustainable land-use alternative for the energy market in Portugal? 17th European Biomass Conference and Exhibition, 29 June – 3 July 2009, CCH-Congress Center, Hamburg, Germany.