



Modelling Carbon Sequestration for Alternative Soil Management Practices of Organic Crop Production

Carolina Ramires Passeira

Dissertation submitted to obtain the degree in
Master in Environmental Engineering – Project

Committee President: Luis Miguel Palma Madeira

(Associate Professor of Chemical Engineering Department at Faculty of Engineering of University of Porto)

Academic Supervisor: Belmira de Almeida Ferreira Neto

(Assistant Professor of Materials and Metallurgic Department at Faculty of Engineering of University of Porto)

Supervisors at Agroscope: Thomas Nemecek (Deputy Leader of the LCA-group at Agroscope Reckenholz-Tänikon Research Station ART) and Michal Kulak (PhD student at LCA-group at Agroscope Reckenholz-Tänikon Research Station ART)

Porto, July of 2012

Integrated Master in Environmental Engineering 2011/2012

Editado por

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO
Rua Dr. Roberto Frias
4200-465 PORTO
Portugal

Tel. +351-22-508 1400

Fax +351-22-508 1440

Correio electrónico: feup@fe.up.pt

Endereço electrónico: <http://www.fe.up.pt>

Reproduções parciais deste documento serão autorizadas na condição que seja mencionado o Autor e feita referência a *Mestrado Integrado em Engenharia do Ambiente – 2011/2012 – Faculdade de Engenharia da Universidade do Porto, Porto, Portugal, 2012.*

As opiniões e informações incluídas neste documento representam unicamente o ponto de vista do respectivo Autor, não podendo o Editor aceitar qualquer responsabilidade legal ou outra em relação a erros ou omissões que possam existir.

To my mother for being my safe harbor.

Acknowledgements

I would like to thank to my academic supervisor Professor Belmira Neto for the useful revisions, all the important inputs, the support and comprehension during my thesis development.

A very special thank you to Dr. Thomas Nemecek for the opportunity you gave me to develop my thesis. I also would like to thank for all the valuable knowledge, for all the time spent and for the patience.

A huge thank you Michal Kulak for all the discussions, time spent, knowledge exchange, useful remarks and, especially, for the patience with me. You were always available. Thank you very much.

I also would like to thank to Professor Daniela Santos, for all the time and availability shown to go with me to the farms and for all the discussions about agricultural practices and improvement strategies.

I would like to thank also to the farmers, Eng. Marco Nunes and Eng. Carmen Staats for the delivered data, the availability to receive me in their farms and the time spent to help me understand all the production processes.

For all the help and time spent discussing carbon sequestration and advises that were very useful to develop my work, I would like to thanks to Jens Leifeld. Without your help I would still be lost in papers.

To Agroscope and specially to Life Cycle Assessment research group that provided all the facilities so the development of this thesis was possible. Thank you for all the contribution and the excelent work environment.

I also would like to thank to SOLIBAM groups for my integration in the project.

To University of Porto for supporting Erasmus Programme and making possible extraordinary work experiences such as the one I had.

To my Mother, the biggest thank you, for all the opportunities, love you gave to me. All the dedication, persistency and advises made me who I am today. Without you, I would not be able to understand the meaning of “never giving up”.

To Micael Pinho, a very special thank you for being by my side, for being everything, for share all the moments with me, from the happiest to the saddest. Without your smile, my world would be colourless.

To my very special friends Maria Fernandes, Joana Correia, Diana Lopes, Susana Santos and Carolina Lucas, because we mean laughter, we mean tears, we mean trust, we mean stupid dances and senseless songs... But, above all the things we mean friendship. Thank you for all the support and experiences that we shared. Without each of you, achieving this new phase would not have as much sense.

To Kasia Lukasiewicz for all the support and friendship during my thesis. Without you, my days would not be so funny and the mountains would not have shined so much.

Abstract

The agriculture is one of the most important sectors responsible for climate change problems. Therefore, it is very important to find ways that can reduce its impacts and make this sector more sustainable. The aim of this thesis is the assessment of the Global Warming Potential over a time frame of 100 years for one farm located in Portugal that produces organic crops and assess the influence Carbon Sequestration for alternative soil management scenarios. To develop this thesis, it was used a Life Cycle Assessment based software - SimaPro 7.3 and the method SALCA (Swiss Agricultural Life Cycle Assessment). The farm studied is located in *Ribatejo Centro* and the organic products in focus are vegetables products (as tomato and broccoli) and grain products (as barley and wheat).

The study here presented compares the influence of carbon sequestration for the conventional and the no-tillage management practices. It is clear that the carbon footprint decreases due to the absence of tillage processes. Decreasing values varied from -10 % to -30 %. Results show that carbon sequestration has a significant influence in terms of carbon footprint. For the whole farm and for the productive unit year the results (period 2008 and 2010) are between -10% and -19% lower than the results from the current tillage process. For the land management unit the results (period 2008 and 2010) are between -10% and -30% lower when reported to the current tillage process.

The scenarios studied (incorporating carbon sequestration rates from a large number of meta-analysis studies collected from the literature) show that the uncertainty associated to the carbon footprint results obtained is large. The uncertainty generated in the field results and the lack of agreement in the carbon sequestration rates is expressed in the results obtained.

Opportunities to extend the work here done are possible as by performing more fieldwork to understand better the effect of different variables (as for example, precipitation, temperature, tillage and crops' type) on carbon sequestration.

Abbreviations

CH₄ – Methane

CO₂ – Carbon Dioxide

CT – Conventional Tillage

EPD – Environmental Product Declarations

EU - European Union

FAO – Food and Agriculture Organization

FP7 - Seventh Framework Programme

GHG - Greenhouse gas

GRI - Global Reporting Initiative

GWP – Global Warming Potential

IPCC – Intergovernmental Panel on Climate Change

iPOM - intra-aggregate Particulate Organic Matter

ISO - International Organization for Standardization

LCA – Life Cycle Assessment

N₂O – Nitrous Oxide

NT – No Tillage

RF – Radiative Forcing

RMPs - Recommended Management Practices

RT – Reduced Tillage

SALCA – Swiss Agricultural Life Cycle Assessment

SOLIBAM - Strategies for Organic and Low-Input Integrated Breeding and Management

SOM – Soil Organic Matter

Table of Contents

1. Introduction	1
1.1. Climate Change and Agriculture.....	1
1.2. Carbon Sequestration in Agriculture.....	2
1.2.1. Carbon Sequestration in Life Cycle Assessment	6
1.3. Short Description of the SOLIBAM Project.....	8
1.4. Thesis Objectives and Goals	9
1.5. Thesis Outline.....	10
2. Carbon Sequestration and Life Cycle Assessment: Literature Revision and Methodology	13
2.1. State of the Art in Carbon Sequestration	13
2.1.1. Effect of Different Tillage Management in Carbon Sequestration.....	13
2.1.2. Fertilizers Inputs and Management	18
2.1.3. Crop Rotation	20
2.1.4. Biochar as Soil Amendment	21
2.2. The LCA Methodology	24
2.3. Description of the Database Swiss Agricultural Life Cycle Assessment (SALCA).....	26
3. Farm description and data collection	27
3.1. General Information.....	27
3.2. Goal and Scope.....	28
3.3. Data Collection	30
3.4. No-tillage Scenario	35
3.5. Carbon Sequestration Scenario.....	36
4. Results and Discussion	39
5. Conclusions and Future Work	45
References.....	49

List of Tables

Table 1 - Radiative Forcing and Global Warming Potentials for a 100-years time horizon from some of the Greenhouse Gases (Mandlebaum and Nriagu, 2011, Maciel et al., 2012).	2
Table 2 - Recommended Management Practices.	5
Table 3 - Effect of tillage management on carbon sequestration.....	16
Table 4 - Results from meta-analyses.	18
Table 5 – Studies of the effect of mineral and organic fertilizer inputs in Carbon Sequestration.	19
Table 7 – Advantages of Biochar application in the soil and Potential Feedstocks.	22
Table 8 - Region climate and soil characterists.	30
Table 9 - Nutrient and Pesticides' inputs for each crop per hectare and year.	31
Table 10 - Crop rotation scheme of Farm 1.	32
Table 11 - Yields per crop.	33
Table 11 - Allocated field area, storage building, pipelines and pump stations.	35
Table 12 – Processes and dates of soil tillage processes, sowing/planting and harvest for each crop.	35
Table 14 - Conversion of Carbon Sequestration Rates, from $\text{ton C.ha}^{-1}.\text{yr}^{-1}$ to $\text{ton CO}_2.\text{ha}^{-1}.\text{yr}^{-1}$	36
Table 15 - Carbon Footprint of each crop expressed in the productive function for the current management practices at the farm and no-tillage scenario.....	40
Table 16 - Carbon Footprint of each crop expressed in the land management function for the current management and for no-tillage scenario.	41
Table 17 - Carbon Footprint of the farm expressed per unit of profit for the whole farm for current management and no-tillage scenario with the reduction percentage of the carbon footprint.	42

List of Figures

Figure 1 - Illustration of carbon pools in annual crop plants (Bolinder et al., 2007).	3
Figure 2 - Carbon cycle above and belowground (adpted from (FAO, 2007)).	4
Figure 3 - Life cycle of macroaggregates and formation of microaggregates (Six et al., 2000)..	15
Figure 4 - Stages of LCA (ISO 14040,2006)	24
Figure 5 - Location of Farm 1.	28
Figure 6 - System Boundaries of Farm 1.	29
Figure 7 - Global warming potential for the productive unit per year, comparing the current management with no-tillage scenario.	43
Figure 8 - Global warming potential for the land management unit, comparing the current management with no-tillage scenario.	43
Figure 9 – Results of the influence of carbon sequestration rates in the no-tillage scenario per each crop, per area.	44
Figure 10 - Results of the influence of carbon sequestration rates in the no-tillage scenario for the whole farm, per area.	44

1. Introduction

1.1. Climate Change and Agriculture

Anthropogenic activities associated with the use of oil and coal together with agricultural practices and deforestation had added considerable quantities of greenhouse gases (GHG) to the atmosphere. Carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) concentrations in air had increased over 31%, 151% and 17%, respectively, between 1750 and 2000 (VijayaVenkataRaman et al., 2012). The growing problem associated with climate change is a clear evidence of these contributions. Effect of sea-level rise, increasing of the global temperature, the oceans warming, the melting of glaciers are the symptoms associated with the climate change (VijayaVenkataRaman et al., 2012, Rogner et al., 2007). In Portugal, evidences of climate change are also clear and since 1970 the mean temperature raised at a rate of 0.45 °C per decade while precipitation values, recorded since 1931, shows an evident reduction (Maciel et al., 2012).

Agriculture is one of the main sectors responsible for the emission of GHG. Some authors state that agriculture is responsible for 10 to 12 % of the global GHG emissions (Niggli et al., 2009). This is equivalent to 5.1 to 6.1 Gt CO₂ equivalents per year. In Europe, food production and consumption are responsible for about one-fourth of the total GHG emissions (Niggli and Scialabba, 2011). The croplands are one of the largest source of carbon loss of all land-use types (VijayaVenkataRaman et al., 2012). Between 1990 and 2005, the emission of methane and nitrous oxide due to agriculture increased by 17% (58 Mt CO₂ equiv. /year) and this is mainly due to biomass burning, enteric fermentation and the emissions of nitrous oxide from soil (Smith et al., 2007). These three sources are in the origin of about 88% of the emission of GHG from agriculture practices.

Methane and nitrous oxide have larger global warming potentials compared to CO₂. However, CO₂ has gained more attention due to its comparatively large concentration in the atmosphere and its larger radiative forcing (RF) (Table 1). Radiative forcing is the net difference between radiation entering and leaving the atmosphere. A positive RF

warms the surface of the earth and a negative RF cools it (Mandlebaum and Nriagu, 2011).

Table 1 - Radiative Forcing and Global Warming Potentials for a 100-years time horizon from some of the Greenhouse Gases (Mandlebaum and Nriagu, 2011, Maciel et al., 2012).

Greenhouse Gases	Radiative Forcing (W.m⁻²)	Global warming potentials for a time horizon of 100-years (CO₂ equiv.) (IPCC, 2007a)
CO₂	1.66	1
CH₄	0.48	25
SF₆	0.004	23 900
N₂O	0.16	298
Halocarbons	0.34	14 800

One of the measures to mitigate GHGs emissions can be achieved by the replacement of fossil fuels by renewable energy. Adoption of these solutions will take a long time and it will be necessary a large investment in research. The usage of energy in an efficient way is also a possibility that depends deeply on people and also in science to create new equipment that can use energy in an efficient way.

For agriculture industry, a way of decreasing GHG emissions is to reduce inputs of fertilizers in the soil and as a recent option, increase carbon sequestration in soils in order to reduce the concentration of carbon dioxide in the atmosphere (Mandlebaum and Nriagu, 2011).

1.2. Carbon Sequestration in Agriculture

Carbon sequestration is a long-term storage of carbon and is an important way to reduce the concentration of carbon dioxide in the atmosphere. There are several possibilities for carbon sinks, such as soil, oceans, rocks, atmosphere and biosphere (Mandlebaum and Nriagu, 2011, ESA, 2000, VijayaVenkataRaman et al., 2012). However, in this work only sequestration due to agricultural soil will be further considered.

Photosynthesis is a process that contributes to the assimilation and retention of carbon in the plant. This carbon can be distributed in four pools (Figure 1) (Bolinder et al., 2007):

- Product (C_P): this part of the plant represents the primary economic value and is typically harvested;
- Straw/Residues (C_S): post-harvest residue aboveground;
- Roots (C_R): root tissue present belowground biomass. This is the part that can be physically recovered (explanation useful to distinguish extra-roots carbon pool);
- Extra-roots (C_E): includes root exudates and other material derived from root-turnover. Physical processes like collecting, sieving or removal are not useful to recover this material. It is important to mention that this material can be referred as rhizodeposition.

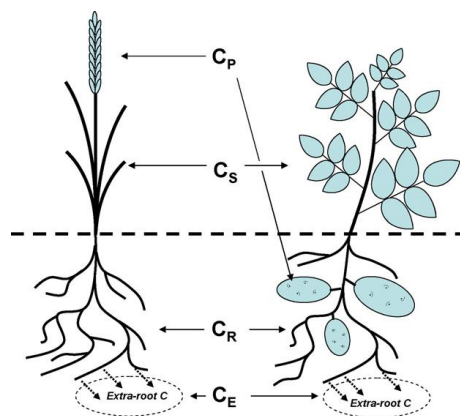


Figure 1 - Illustration of carbon pools in annual crop plants (Bolinder et al., 2007).

The carbon stored in the products cannot be counted as a pool because it will be consumed and lost. However, residues from the harvest process can be incorporated in the soil. These residues will decompose and will be converted into Soil Organic Matter (SOM), which is a mixture of carbon compounds obtained through the decomposition of plants and animals, microbes and carbon existing in the soil minerals (ESA, 2000).

Figure 2 shows carbon cycle in crops and forests. In the forest, all the carbon present in the wood is out of the carbon cycle for a long time. This means that carbon is stored in

its tissues as long as they are not cut off. Annual crop plants play a different role in the carbon cycle. While they are growing, plant tissues are built up and carbon is stored until its harvest. After this process, carbon from products is lost and straw and roots can be left in the soil. The inherent decomposition of this material leads to SOM formation and consequently is used as nutrient supply to other species. It can also mineralize or be lost as gaseous (in form of CO_2). When converted to CO_2 , this compound can be used, again, to build up more plant tissues and re-start the cycle.

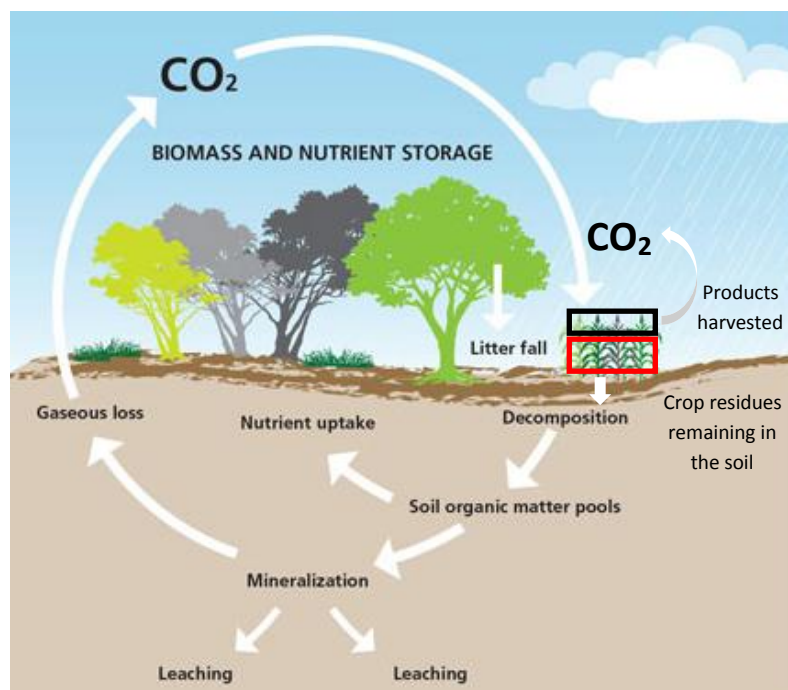


Figure 2 - Carbon cycle above and belowground (adapted from (FAO, 2007)).

To maintain and increase the carbon content in soil is necessary to increase the carbon input and/or decrease its output (in the form of emissions and leaching). This can be achieved through improved management soil practices (Jarecki and Lal, 2003, Freibauer et al., 2004). Many studies refer to Recommended Management Practices (RMPs) for carbon inclusion into the soil, such as conservation tillage, organic matter input, production of perennial crops and promotion of crop rotation systems (Lal, 2004, Freibauer et al., 2004, Smith, 2004, VijayaVenkataRaman et al., 2012). Table 2 identifies and summarises some of these RMPs. Most of them are identified by the Food and Agriculture Organization of the United Nations (FAO) (Niggli et al., 2009).

Table 2 - Recommended Management Practices.

Recommended Management Practices	
Conservation Tillage	This practice is based on avoiding full inversion and deep tillage. This means a complete no-tillage (direct sowing) or reduced tillage that consists on applying chisel machinery (used only to break compact soil without inverting the soil). It reduces soil disturbance by avoiding deep tillage.
Perennial crops	This practice is carried out only by using permanent crops. This means that once it is sown or planted, can live for many years. Trees and shrubs are considered as perennial crops. Perennial crops are beneficial to reduce soil erosion, minimize nutrient leaching and sequester more carbon in soil. This last advantage is explained by longer growing seasons, more extensive roots and non-cutting system which are beneficial to keep carbon in above ground mass. (Zhang et al., 2011)
Crop rotation	It is important to promote different types of crops, that grows in different seasons (summer and winter crops) to avoid fallow seasons. When different species are growing, it is possible to achieve different depths in the soil. For example: grain species like wheat or barley grow roots in the entire soil profile (0-100 cm). On the other hand, leguminous species (soybeans) can achieve only 60 cm of depth. This means that when different types of crops are produced, the entire soil profile can have organic carbon from the belowground biomass (roots).
Use organic fertilizers	The usage of organic fertilizers has many benefits in terms of soil quality. It can prevent erosion and retain water in the soil. Using cover crops, as green fertilizers, is important to fix nitrogen in the soil, avoiding the need of mineral fertilizers. Besides this fact, organic products have a large amount organic matter in their composition, which is important for soil carbon sequestration.

Table 2 - Recommended Management Practices.

Irrigation	Similar to organic fertilizers, the amount of water incorporated in the soil can enhance biomass production, increasing above and belowground biomass and improve SOC. Moreover, the optimization of the process can prevent the usage of machinery and consequently, the amount of fuel burned. (Lal, 2004) However, the inclusion of large amounts of water (in a non-optimized irrigation system) can increase the leaching of nitrogen, phosphorous and organic matter, decreasing the carbon pool.
Integration of livestock with crop production	If a farm has animal production, farmers will use manure from livestock. Such situation avoids fertilizer inputs from the outside of the farm. In a life cycle perspective, transport's impact would decrease. On the other hand, the use of manure as fertilizer increases methane emissions.
Integration of Biochar as soil amendment	Biochar is a carbon-rich product of biomass pyrolysis that is recently being studied as a soil amendment. It is estimated that the approximate mean residence time in soil of this product is about 1000 years. (Vaccari et al., 2011)

Although many practices are recommended, not all are studied. Many experimental studies focus on the influence of tillage, fertilizer inputs and crop rotations systems in soils. On this thesis, these three management practices were studied. However, only one (no-tillage effects) could be applied to the current case study.

1.2.1. Carbon Sequestration in Life Cycle Assessment

Life Cycle Assessment (LCA) is an internationally recognised method to assess environmental impacts of products and services. According to FAO, the influence of the crop rotation effects, the soil carbon sequestration and the land use in the farming system is not currently assessed (Niggli and Scialabba, 2011). However, studies developed in Agroscope include land use change effects. Besides, a number of LCA studies have recently addressed carbon sequestration considerations into LCA results.

Some of them are presented below. A study was performed, in Denmark, mainly to suggest a methodological approach to estimate the effect of soil carbon changes on CO₂ present in atmosphere, in order to be included in LCA results. A modelling tool (C-TOOL) was used to analyse the differences on soil carbon estimates along the time (20, 100 and 200 years) and its relation to the soil profile (0-100 cm). This model includes three types of carbon pools in soil:

- Fresh Organic Matter (FOM) – new organic matter provided by crop residues or manure;
- Humus (HUM) – native organic matter;
- Microbial biomass.

Each pool exhibits first-order decay, which means that they are only dependent on the concentration of carbon. Besides, the model also contemplates transport of C from topsoil to subsoil. On the other hand, Bern Carbon Cycle Model (IPCC, 2007b) describes the decay curve of C released from the soil to the atmosphere. The combination of the two models plus decay model of C in the atmosphere, gives us the balance of C and consequently the emissions/sequestration from/on the soil. The results of these models, per year, were added to LCA results for two different situations. This addition was done without any model of inclusion carbon changes in LCA. It is also important to clarify that this study pointed some limitations on LCA method such as time-related conditions. Once carbon balance depends deeply on time, it makes difficult to include this effect on LCA.

Brandão et al. (2011) assessed the impact of soil organic carbon changes in the cultivation of energy crops, in United Kingdom. For that, four types of land use were considered: oilseed rape production (firstly farmed for human consumption, it is becoming popular for energy purposes), miscanthus (known as elephant grass, is a perennial energy and fibre crop), willow under a short-rotation coppice (fast-growing perennial woody crop that can be used as a fuel for heat and power generation) and forest residues (poor quality forest material without any functionality for traditional timber markets). Data from carbon sequestration rates for each type of land use was taken from the reviewed literature (Brandão et al., 2011).

Malça and Freire (2012) studied the production of wheat in order to produce bioethanol (Malça and Freire, 2012). The main goal of the study was to evaluate different scenarios for land use change: improved grassland converted to wheat production; full tillage, low input cropland switched to wheat cultivation; low tillage, medium input cropland converted to wheat cultivation. In order to calculate land use change, IPCC guidelines were used and addressed to carbon footprint of wheat-based ethanol production. Results show that GHG emissions have a larger uncertainty than energy renewability because of soil carbon emissions from direct land use change and nitrous oxide release from cultivated soil (Malça and Freire, 2012).

In the studies performed at Agroscope, land use change is already included due to the usage of IPCC guidelines in the Swiss Agricultural Life Cycle Assessment (SALCA) method.

In summary, it is possible to say that all the studies reviewed show different ways to predict carbon storage in agricultural products. However, no methodology or model has been developed to include these results into LCA.

1.3. Short Description of the SOLIBAM Project

According to FAO, in 2050, agricultural production should increase by 70% (Niggli et al., 2009). For that reason, it is extremely important to find systems that are sustainable in an environmental point of view and develop new techniques and strategies of production.

The work carried out in this thesis is part of a project designated by Strategies for Organic and Low-Input Integrated Breeding and Management (SOLIBAM). This is a collaborative project from the EU Seventh Framework Programme (FP7) 2010-2015 and the objective is *“to develop novel breeding approaches integrated with management practices to improve the performance, quality, sustainability and stability of crops adapted to organic and low-input systems in Europe and Sub-Saharan Africa”* (SOLIBAM, 2010a). The project has 23 partners along Europe and Africa (France, Italy, Portugal, United Kingdom, Germany, Austria, Spain, Denmark, Hungary, Switzerland, Mali and Ethiopia).

This thesis was carried out in the Life Cycle Assessment Research Group at Agroscope Reckenholz-Tänikon Research Station ART, located in Zurich, Switzerland. ART is a partner of the SOLIBAM consortium.

The SOLIBAM project aims at assessing the environmental and socio-economic impacts of new strategies and techniques of crop production, compared with current agricultural practices. In addition, these results will support, according to local context, recommendations for legal regulations, which are required to adopt the innovative breeding strategies, to determine financial impacts on farming business and to quantify overall changes in cost structures (SOLIBAM, 2010b). The results are obtained by considering the practices from eight case study farms located in Portugal, Italy, United Kingdom and France.

The developed work was integrated in the SOLIBAM project, at the Life Cycle Assessment group of ART. The responsibility of the group within the project is the assessment of the environmental impacts of agricultural systems. This work helped on data collection and information treatment from the two farms in Portugal. However, only one farm's information was used because of late data delivery. For confidentiality reasons, the farm used in this study will be further called Farm 1.

1.4. Thesis Objectives and Goals

The objective of this thesis is to evaluate the influence of carbon sequestration in soil management practices for a Portuguese farm. This study considers the inventory from 2008 to 2010. During that period Farm 1 produced wheat, barley, tomato and broccoli on crop rotation system and under organic farming. The farm used horse manure combined with other organic fertilizers and pests controllers.

The inventory considered the current technique applied for the soil management (conventional tillage: harrowing, subsoil machine and ploughing) and the alternative management scenario (no-tillage). The influence of carbon sequestration for these two soil management practices was compared in terms of carbon dioxide equivalent emissions.

1.5. Thesis Outline

This chapter reveals some of the concerns of climate change associated to agricultural practices. It also explains carbon sequestration and illustrates some of the recommended management practices to increase organic carbon in soils. A revision of the available literature is made on the incorporation of carbon stock changes in life cycle assessment studies. It is also shortly described that this project is carried out under a task from a European project. At the end, the objectives and goals are identified and the dissertation structure described.

Chapter 2 focuses on the literature review for carbon sequestration associated to soil management practices. The theoretical concepts associated to the methodology used in this project (Life Cycle Assessment) are described. Also the Swiss Agricultural Life Cycle Assessment-SALCA that is the database and method used in the inventory and impact assessment.

Chapter 3 describes the farm and its agricultural management practices. The region where the farm is located is identified and also is the goal and scope of the study. The functional units and system boundaries are described as well as the data collected and the calculations for the Global Warming Potential of the farm is presented. The information like soil characteristics and all the management practices such as soil tillage, fertilizers, crops' identification and crop rotation are included in this chapter as well as all the assumptions and scenarios carried out to develop no-tillage scenario and the carbon sequestration input.

Chapter 4 presents the LCA results specifically for the global warming potential. Results are presented for each crop and year using three functional units related to production, land usage and profit value. Results are presented for the current management practices and for the no-tillage scenario. The carbon sequestration rates used in the conversion from conventional tillage to the no-tillage scenario are included.

Chapter 5 draws the conclusions of the study. Moreover, some future work recommendations are presented. This relates to management practices, limitations associated to the methodology used, learned lessons and guidelines for future work in this field.

2. Carbon Sequestration and Life Cycle Assessment: Literature Revision and Methodology

Many authors recommend a wide variety of sustainable practices, in order to sequester and maintain carbon in agricultural soils. This chapter reveals and discusses a few reviewed experimental studies and expertise's opinions on the relation of carbon sequestration to several tillage practices, crop rotation systems, fertilizers and the inclusion of biochar in soil.

2.1.State of the Art in Carbon Sequestration

2.1.1. Effect of Different Tillage Management in Carbon Sequestration

A selection of studies based on field experiments from long-term experiments (10+ years) was revised in order to investigate the influence of the tillage practices in carbon sequestration.

Some authors state that no tillage (NT) practices can increase soil organic carbon when compared to reduced tillage (RT) or conventional tillage (CT) (Deen and Kataki, 2003, Six et al., 2004, Olson et al., 2005, Hernanz et al., 2009, Ussiri and Lal, 2009, Sombrero and de Benito, 2010, Mazzoncini et al., 2011).

Climate conditions like rainfall and temperature are claimed to be one of the factors that influences tillage effects on carbon sequestration rates. Some authors believe that under cold and moist climates, the no-tillage practice is not as promising as in tropical, sub-tropical and semi-arid regions (Angers et al., 1997, Six et al., 2004, Carter, 2005, Zinn et al., 2005, Hernanz et al., 2009). In addition, no tillage is only effective on top soil (0-40 cm), while CT can achieve higher depths in the soil (Deen and Kataki, 2003, Mahdi M. Al-Kaisi, 2005, Gaiser et al., 2009, Luo et al., 2010). However, for many years comparisons between conventional and no-tillage were done based on top soil samples which influenced deeply the conclusions about the effects of each tillage management.

Six et al. (2000) created a model in order to explain the effect on carbon sequestration for different types of tillage by conducting field experiment in macro and

microaggregates (Six et al., 2000). Macro and microaggregates are defined as aggregated soil material and differs on size. The study developed a model that shows the influence of NT and CT in the formation of the aggregations. The model presented in Figure 3 is the base for the hypotheses tested in the study (Six et al., 2000). The inclusion of fresh residues, as for instance, crop residues and manure, as a fertilizer in soil, contributes for the formation of macroaggregates with a dimension of 250-2000 mm. In the following, the description of the formation of micro and macro aggregates and its relation to the carbon sequestration is described.

When the fresh matter is added to the soil, an outside layer of fresh residue is created (t_1). The residue input is often similar for conventional and no-tillage management systems. Between t_1 and t_2 , decomposition inside of the macroaggregates origin fine particulates of organic matter. When conventional tillage is performed at this stage, the young and unstable macroaggregate breaks and leads to the emission of carbon dioxide. Furthermore, the formation of the macroaggregates also produces carbon dioxide due to microbial activity. However, these emissions are comparatively much lower (Six et al., 2000). Between t_2 and t_3 the outside part of the macroaggregate becomes encrusted with clay particles and microbial products in order to form microaggregates within macroaggregates. Eventually, the binding agents in macroaggregates break, resulting in loss of macroaggregate stability (t_4) and the release of stable microaggregates. This will be the base building blocks for the next cycle of macroaggregate formation. The model suggests that the increase in soil disturbance induced by soil tillage creates less new stable microaggregates and, for that reason, the availability of material to create new macroaggregates reduces (Six et al., 2000). As this material is composed by carbon, the potential of carbon sequestration is lower.

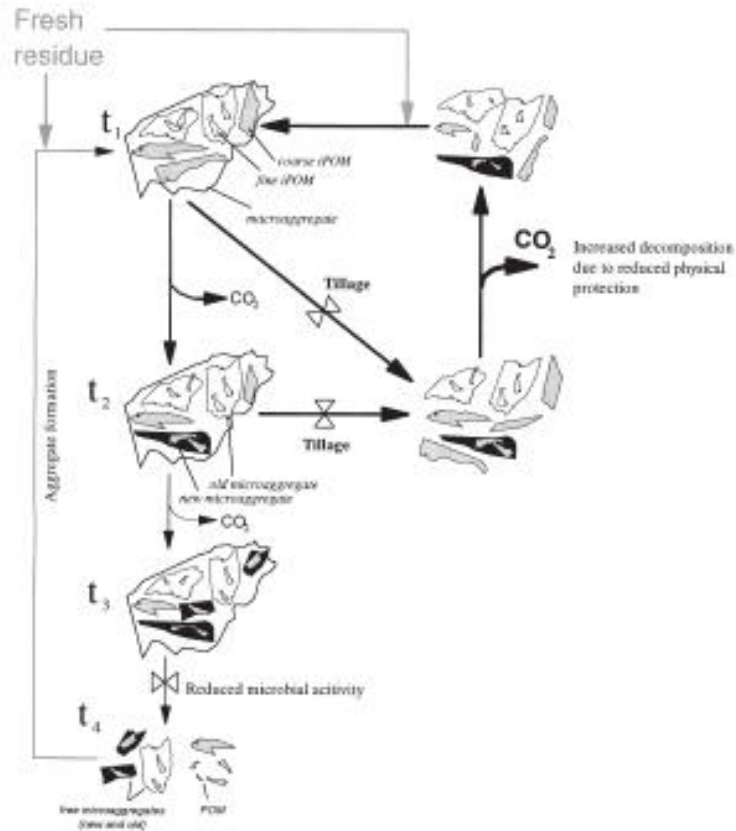


Figure 3 - Life cycle of macroaggregates and formation of microaggregates (Six et al., 2000).

Table 3 lists a selection of studies that refer to the tillage effect on carbon sequestration rates. Results obtained by the different authors are not consensual. Sequestration rates for no-tillage varies from -0.43 to $6.05 \text{ ton C.ha}^{-1}.\text{yr}^{-1}$, while for conventional tillage, the variation is presented between -1.14 to $5.69 \text{ ton C.ha}^{-1}.\text{yr}^{-1}$.

Table 3 - Effect of tillage management on carbon sequestration.

Study reference	Years	Soil depth	Crops and crop rotation	Carbon sequestration rates (ton C.ha ⁻¹ .yr ⁻¹)		
				No-tillage	Reduced Tillage	Conventional Tillage
(Sainju et al., 2008)	10	0-20 cm	Crop rotation of corn-cotton-rye	0.1 – 0.51	0.4	-0.12 - 0.51
(Mazzocini et al., 2011)	15	0-30 cm	Non continuous corn-wheat-sunflower	0.61	-	-0.06
(Ussiri et al., 2009)	43	0-30 cm	Continuous corn	1.37	0.71	0.73
(Sombrero and Benito, 2010)	10	0-30 cm	Legume and cereal crops	1.78	1.33	0.46
(Dolan et al., 2006)	23	0-45 cm	Maize and soybean	4.7	9.7 – 11.7	4.7 – 5.1
(Olson et al., 2005)	12	0-75 cm	Maize-soybean	-0.43	-0.68	-1.14
(Gál et al., 2007)	28	0-100 cm	Corn and soybean	6.05	-	5.69

Note: Negative values mean emissions.

Although the literature review performed on single studies was important to understand the differences in the carbon sequestration rates for different soil management options, meta-analyses were studied in order to cover more experimental results. Table 4 shows the results collected from four meta-analyses.

The work from West and Post (2002) results in a global data analysis based on 67 long-term agricultural experiment sites, consisting on 276-paired treatments between conventional and no-tillage management. The analysis considered soil depth between 0 and 35 cm and results showed a sequestration of carbon of 0.48 ton C.ha⁻¹.yr⁻¹.

Alvarez (2005) studied about 76-paired field experiments which soil depth study was between 0 and 60 cm. To integrate this meta-analysis, nitrogen rates and tillage

management were the only variables presented in each field experiment. Besides, residues should not be removed from the field and soil organic carbon mass per unit area and bulk density were reported. The author concluded that the no-tillage increases soil organic carbon under a sequestration rate of $0.26 \text{ ton C.ha}^{-1}\text{.yr}^{-1}$. However, this evidence is only clear when no-tillage practice is used for long periods.

Luo et al. (2010) collected and reviewed 69-paired conventional and no-tillage experiments. The criteria used was based on soil depth samples that should be deeper than 40 cm and management should be similar to no-tillage and conventional tillage trials, in terms of cropping system, fertilization and irrigation. It was possible to conclude that no-tillage leads to a decrease in soil carbon stocks when compared to conventional tillage management ($-0.15 \text{ ton C.ha}^{-1}\text{.yr}^{-1}$).

Angers and Eriksen-Hamel (2008) studied 23 field studies comparing no-tillage and conventional tillage. Replications of experimental designs on the same soil type and depth samples larger than 30 cm were one of the criteria for studies collection, for this meta-analysis. Besides, each study should have the same management in terms of crops used, fertilization rates and residue management. As last condition, tillage treatments should have been applied for at least 5 years.

Besides sequestration rates, the authors stated some other conclusions. Luo et al. (2010) concluded that below 40 cm, no significant difference was found between conventional and no-tillage management. Moreover, no relation between climate conditions (e.g. temperature, rainfall...), no-tillage duration practices and nitrogen fertilization rates were found to be significant to the effects in carbon sequestration rates (Alvarez, 2005, Luo et al., 2010). On the other hand, Angers and Eriksen-Hamel (2008) found a significant relation between no-tillage results and climate (Angers and Eriksen-Hamel, 2008).

While Luo et al., (2010) found that no-tillage results, on carbon sequestration, increase with double cropping systems, Alvarez et al. (2005) conclude that any kind of cropping system affect no-tillage results (Alvarez, 2005, Luo et al., 2010).

Angers and Eriksen-Hamel (2008) suggest that under no-tillage management the fuel consumption, obviously, decreases while fertilizers and herbicides inputs increase. This means that, although carbon dioxide emissions reduce, emissions of nitrous oxide will

increase (Angers and Eriksen-Hamel, 2008). Herbicides are needed in order to control weed growth.

Generally, some authors reveal the need of deeper soil sampling in order to assess a more robust influence of conventional and no-tillage on carbon sequestration (Alvarez, 2005, Angers and Eriksen-Hamel, 2008, Luo et al., 2010). For that reason, West and Post (2002) study might have been super estimated.

The results from meta-analyses allow concluding that the controversial results persist in the meta-analyses conclusions. As such, it is again highlight the need of conducting more studies to evaluate a more supported effect of tillage managements on carbon sequestration.

Table 4 - Results from meta-analyses.

Reference	Number of studies	Minimum and maximum study lenght considered	Soil depth	Conversion from CT to NT
				(ton C.ha ⁻¹ .yr ⁻¹)
(West and Post, 2002)	67	6-69 years	0-35 cm	0.48
(Alvarez, 2005)	76	1-30 years	0-60 cm	0.26
(Luo et al., 2010)	69	3-29 years	0-60 cm	-0.15
(Angers and Eriksen-Hamel, 2008)	23	5-42 years	0-90 cm	0.31

In summary, despite that fact that there is no definitive conclusion about the relation of no-tillage practice and carbon sequestration rates, it is clear that this management option protects the soils against erosion, reduces the production costs and decrease the consumption of fossil fuels needed by comparison to CT (Baker et al., 2007).

2.1.2. Fertilizers Inputs and Management

Table 5 shows a list of long-term experimental fields that evaluates the effects of mineral and organic fertilization, separately and in combination. In the following the details referring to the amount, types of fertilizes used (manure or mineral) and carbon sequestration is provided for each study.

Table 5 – Studies of the effect of mineral and organic fertilizer inputs in Carbon Sequestration.

Reference	Soil depth	Years of the study
(Lou et al., 2011)	0-20 cm	22
(Purakayastha et al., 2008)	0-45 cm	32
(Hati et al., 2008)	0-45 cm	29
(Zhai et al., 2011)	0-20 cm	16
(Mazzoncini et al., 2011)	0-30 cm	15
(Dolan et al., 2006)	0-45 cm	23
(Kukal et al., 2009)	0-60 cm	32
(Gong et al., 2009)	0-20 cm	18

Lou et al. (2011) studied the effect of different fertilizers management for 22 years: manure input under a rate of $135 \text{ kg N.ha}^{-1}.\text{yr}^{-1}$, mineral fertilizer under the same rate and a combination of both types of fertilizer $67.5 \text{ kg N.ha}^{-1}.\text{yr}^{-1}$ each. Results show that application of manure is more efficient ($0.48 \text{ ton C.ha}^{-1}.\text{yr}^{-1}$), in terms of carbon sequestration, than any other option. However, manure combined with mineral fertilizer showed also a large rate for carbon sequestration ($0.3 \text{ ton C.ha}^{-1}.\text{yr}^{-1}$).

Purakayastha et al. (2008) studied, for 32 years, seven fertilizer treatments: 50 % NPK ($130:35:41 \text{ kg.ha}^{-1}$); 100 % NPK ($260:70:82 \text{ kg.ha}^{-1}$); 150 % NPK ($390:105:123 \text{ kg.ha}^{-1}$); 100 % NP ($130:35 \text{ kg.ha}^{-1}$); 100 % N (130 kg.ha^{-1}); FYM + 100 % NPK ($15 \text{ ton.ha}^{-1} + 260:70:82 \text{ kg.ha}^{-1}$). Is important to refer that NPK is a mineral fertilizer that contains nitrogen, phosphorous and potassium, spread with different rates, and FYM is farmyard manure. For this study it was concluded that combination of farmyard manure and mineral fertilizers was the best option, because the mineral fertilization guarantees larger production yields, while from manure input, larger carbon is returned to the soil, increasing soil organic carbon (Purakayastha et al., 2008).

Hati et al. (2008) developed a 29-years field experiment with the inclusion of various rates of fertilizers for a wheat-soybean rotation. The treatments selected were control (CON, where crops were raised without any nutrient application), nitrogen fertilization (NIT), nitrogen and phosphorus (NP), NP plus potassium (NPK), NPK plus manure (NPKM) and NPK and lime (NPKL). For soybean, fertilizer scheme was: NIT (25 kg N.ha^{-1})

¹); NP (25 kg N.ha⁻¹; 26.2 kg P.ha⁻¹); NPK (25 kg N.ha⁻¹; 26.2 kg P.ha⁻¹; 33.3 kg K.ha⁻¹); NPKL (25 kg N.ha⁻¹; 26.2 kg P.ha⁻¹; 33.3 kg K.ha⁻¹); NPKM (90 kg N.ha⁻¹; 51.2 kg P.ha⁻¹; 78.3 kg K.ha⁻¹; 2050 kg C.ha⁻¹). For wheat, the input management was different: NIT (80 kg N.ha⁻¹); NP (80 kg N.ha⁻¹; 26.2 kg P.ha⁻¹); NPK (80 kg N.ha⁻¹; 26.2 kg P.ha⁻¹; 33.3 kg K.ha⁻¹); NPKL (80 kg N.ha⁻¹; 26.2 kg P.ha⁻¹; 33.3 kg K.ha⁻¹); NPKM (80 kg N.ha⁻¹; 26.2 kg P.ha⁻¹; 33.3 kg K.ha⁻¹). Manure was applied once a year, before soybean crop. From this study was concluded that mineral fertilizer associated to manure input leads to a larger value on carbon soil change (0.25 ton C.ha⁻¹.yr⁻¹). In the same way, lime application with mineral fertilizer has a similar rate of carbon sequestration (0.23 ton C.ha⁻¹.yr⁻¹). Both applications lead to an increase of crop yields. Lime input promotes pH correction, which is beneficial to the soil physical condition. Application of fertilizer-N alone, reduced yields of both crops to levels lower than control (any fertilizer or lime application) and adversely affected physical quality of the soil and had a low rate of carbon sequestration.

The studies carried by Dolan et al. (2006), Kukal et al. (2009) and Gong et al. (2009) shows different rates of fertilization on long-term field experiments. The authors concluded from their studies that organic matter from manure is a great contribution from carbon sequestration.

Although all this studies are useful and interesting, the large differences between management, considered crops and fertilizer rates input make the comparison between studies somehow difficult. Of course, the literature review did not cover a large number of the studies published but it is clear that a certain type of standardized method to compare results should be developed.

2.1.3. Crop Rotation

Crop rotation and double cropping systems are essential to improve soil quality and yield of the crops (McConkey et al., 2003, Sainju et al., 2008). In addition, this management helps to increase soil organic matter and contributes for carbon sequestration. This idea is supported by some authors that concluded that under no-tillage systems, double cropping systems and continuous cropping helps to increase

soil organic carbon (Hernanz et al., 2009, Luo et al., 2010, Sombrero and de Benito, 2010). However, in crop rotation's studies, differences between tillage management, fertilizers rate and diversification types of crops are common. These differences do not allow a conclusive comparison.

2.1.4. Biochar as Soil Amendment

Another option to carbon sequestration is possible through the application of biochar as a soil amendment. Biochar is a carbon-rich product produced by the pyrolysis of biomass. This is possible through a thermal decomposition of organic material with limited supply of oxygen at relatively low temperatures (<700 °C). A study refers that its global implementation may offset 12% of current anthropogenic CO₂-C equivalent emission (Vaccari et al., 2011). This product also shows a greater long-term stability compared with fresh organic matter and its mean residence time in the soil is estimated to be more than 1000 years (Vaccari et al., 2011, Barrow, 2012). According to Barrow (2012), biochar quality varies significantly depending on raw material and pyrolysis conditions mainly because there are no standards for its production (Barrow, 2012). The same paper also highlighted some possible advantages from application of biochar and some promising biochar feedstocks. Table 6 shows some of those advantages and current feedstocks.

Table 6 – Advantages of Biochar application in the soil and Potential Feedstocks.

Advantages of Biochar application	Potential Feedstocks
• Enhance plant growth; • Raise of crop yields; • Reduce the need of organic and mineral fertilizers; • Reduce of soil acidity; • Improvement of moisture retention, reducing the demand for irrigation; • Suppress methane and nitrous oxide emission from cultivated soil; • Storage of carbon in soil.	• Cattle, poultry and pig manure; • Wood waste from forestry; • Paper pulp manufacture; • Sewage and poor quality surface or groundwater; • Agricultural production residues.

Roberts et al. (2010) performed a life cycle assessment study on biochar production. The main goal was to assess cumulative energy, climate change impacts and economics of biochar production. The raw material used was corn stover, yard waste and switchgrass feedstock. For corn stover production, data was collected from a study, performed in 2009 and two scenarios based on late and early stover were performed. Yard waste was assumed to be diverted from an industrial-scale composting facility and no environmental problems were addressed. For bioenergy crops (switchgrass), two scenarios were performed in order to study the impact of land-use change. These two scenarios are based in two different models: switchgrass A uses life-cycle emissions model for land use, fertilizer and cultivation related emissions while switchgrass B uses a worldwide agricultural model for land use change from Searchinger et al. (2008).

As a result, for cumulative energy is possible to conclude net energy of the system is positive. This means that more energy is generated than consumed for all scenarios. In terms of GHG emissions, only switchgrass B scenario showed a positive GHG emissions net (emissions larger than reductions). The author explains this difference based on land-use change impact on climate change impact. For economic analysis, it is shown a high uncertainty. However, results highlight the potential revenue when yard waste is used (Roberts et al., 2010). Despite the potential associated to the use of biochar

long-term field experiments are needed to describe the real effects of biochar on production yields and emissions. For that reason, scenarios based on biochar application were not taken into account in this work.

Concluding about the literature review, it is possible to say that many management practices are recommended. However, not all were possible to study due to the focus of published literature.

As it was discussed, mineral fertilizers combined with organic matter are the best option in terms of fertilization systems when the carbon sequestration is of concern. Fertilizer inputs increases yields of crop production and, consequently more root growing, while organic matter provides carbon to the soil. Both facts lead to an increasing on carbon sequestration rates. However, the case study considered in this thesis does not allow the incorporation of mineral fertilizers (management under organic farming).

In terms of tillage practices, there are many opinions that no-tillage management is the best option to increase soil organic carbon. However, the results from the meta-analyses show a concern about soil depth considered. For many years, soil top layer was used to compare conventional and no-tillage. The larger carbon sequestration rates reported from that comparison might be an artefact from soil depth considered because when residues are kept in the top soil (under no-tillage) the largest amount of carbon storage is expected to be in this layer. However, when the entire profile is evaluated, no significant changes between tillage managements are reported. This is due to the inclusion of crop residues, manure and other fertilizers, at the bottom layer of conventional tillage (30 cm), which means that carbon storage occurs from this depth to 90 cm.

For crop rotation, the crops used are very different. This leads to an increased difficulty to evaluate the influence of crops and crop rotation systems in carbon sequestration.

All these results are an important contribution for the study of carbon sequestration and in order to develop more sustainable agricultural practices, the inclusion of agriculture business in carbon market has been discussed as a way of stimulus and compensation for using of the RMPs (Niggli and Scialabba, 2011).

2.2. The LCA Methodology

Life Cycle Assessment is a standard and an internationally recognised method to assess environmental impacts of products and services. The methodology includes four phases, namely, the goal and scope definition, the inventory analysis, the impact assessment and finally the interpretation. The method is standardised using EN ISO 14040:2006 (ISO 14040, 2006).

The goal and scope definition phase defines the entire project and it is deeply connected to the final application of the study and the intended audience. It is necessary to define the functional unit, system boundaries, data requirements and which impact categories and methodology will be taken to assess the environmental impacts of a product or service. The functional unit quantifies the performance of a product system for use as a reference unit. If the study is about a farm, the functional unit can be e.g. 1 kg of a product or the cultivation of 1 hectare during 1 year. The system boundary specifies which unit process is part of a product system. In other words, it specifies the boundaries of the study.

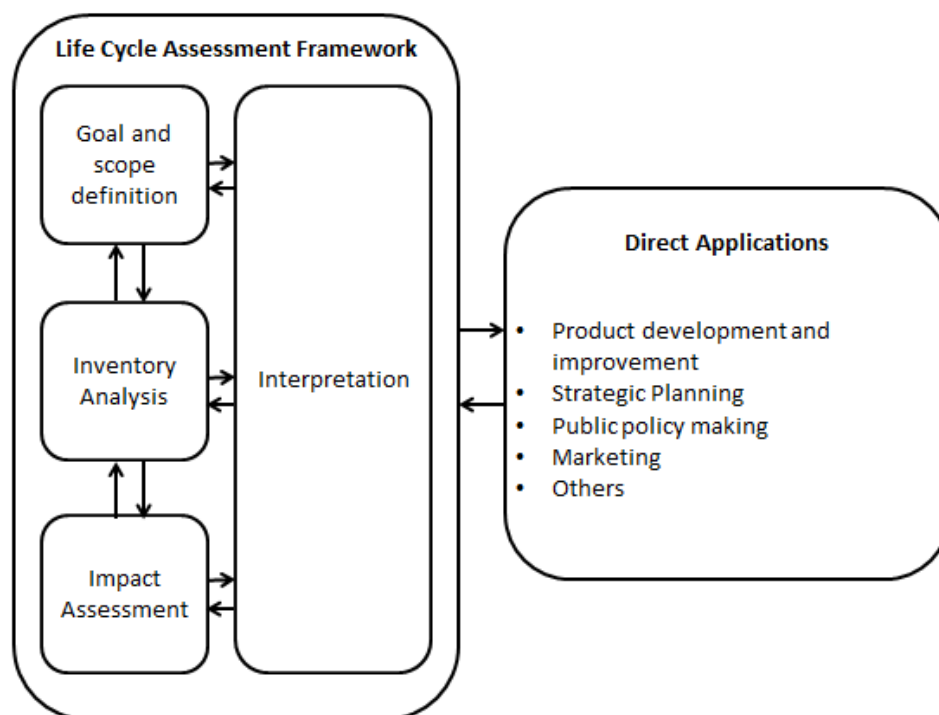


Figure 4 - Stages of LCA (ISO 14040,2006)

The inventory analysis uses data associated to relevant inputs and outputs of the system considered. Data collection must include energy use, raw material, products, co-products and waste material, emissions to air, soil and water and other aspects environmentally relevant. The inventory process is iterative and collecting data helps to acquire knowledge of the project, which can be used to define different boundaries and objectives for the project.

The impact assessment is related to the evaluation of potential environmental impacts using the results of the previous phase. The association of the inventory data with category indicators and specific environmental impact categories gives the opportunity to quantify these impacts. The choice of the model approach and evaluation may create some uncertainty of the results. Therefore, transparency is the most important characteristic of this phase to ensure that assumptions are clearly described and reported. The impact categories are the environmental issues of concern to which life cycle inventory analysis results may be assigned. The impact category indicator is a quantifiable representation of one impact category.

The last phase is the interpretation. For this step it is important to understand the process studied, the data collected and the results obtained from the impact assessment phase. The main objective is to combine the results with the knowledge of the process. With this connection it is possible to understand which phase of the production is causing the biggest contribution for the environmental impact. It is important to deliver results that meet the defined goal and scope. It is also intended that this phase obtain conclusions, explain limitations, provide, and justify possible recommendations.

SimaPro is a LCA based tool that allows calculations of environmental impacts.(Pré-consultants, 2012). This tool includes several databases containing information about life cycle inventories of a wide number of product and processes. This database has over 4000 industrial processes in sectors like energy, transport, building materials, chemicals, washing agents, paper and board, agriculture and waste management.

2.3. Description of the Database Swiss Agricultural Life Cycle Assessment (SALCA)

SALCA is a tool to assess environmental impacts of agricultural systems. Within this framework, the calculation tools SALCAcrop and SALCAfarm allow, respectively, calculations for dozens of crops and farms (Nemecek et al., 2010).

The SALCAfarm treats all types of farms and it is also appropriated to calculate product LCAs like for animal products in a considered period of one year (Nemecek et al., 2010). However, this tool was not used in this work.

The SALCAcrop covers about 140 arable crops, vegetables, permanent crops as well as different types of grassland, animal pasturing and takes into account crop rotations (Nemecek et al., 2010).

SALCAcrop was the tool used in this thesis. At first, the life cycle inventory collected is included in an excel spreadsheet. After, an excel macro is run in order to calculate emissions for nitrate, phosphorous, heavy metals and other field emissions. The resulting file is converted to an EcoSpold file and, finally, imported to SimaPro. The method used to assess the carbon footprint was the GWP over 100 years according to (IPCC, 2007a).

3. Farm description and data collection

In Portugal, the agricultural sector plays an important social role. The agricultural sector employs about 11 % of the total employment rates. However, its gross value added in 2010 was only about 2.3 %, including the activities from forestry and fisheries. Half of the national territory is dominated by agricultural areas, but about three quarters of that area are small farms (Global, 2011).

3.1. General Information

To include SOLIBAM European project, several farms, from different countries, were chosen. There are two farms from United Kingdom, two from France, two from Portugal and two from Italy. Although there are two farms in Portugal, only one was used for this thesis. The late data delivered was responsible for the exclusion of one of the farms. The farm used in this work will be further called Farm 1.

Farm 1 is located in *Ribatejo Centro* (Figure 5). This region is characterized by a dry temperate climate with a precipitation between 700 and 800 mm per year and medium temperature between 15 and 17.5 °C (Ambiente).



Figure 5 - Location of Farm 1.

According to the FAO's nomenclature for soil characterization, Farm 1 is located in a region of Cambisols. These types of soil does not have a large content of clay or organic matter (Hidraulica, 2010).

3.2. Goal and Scope

As an iterative method, the Life Cycle Assessment methodology establishes the need of defining scope and goal of the study, system boundaries and functional units. These processes help in the inventory data collection and keep the focus of the study. However, during the project, the initial definitions can change in order to look for the best analysis of the study.

For the case study presented in this report, the aim was to assess the GWP over 100-year horizon of a farm in Portugal that is responsible for the production of tomato, broccoli, wheat and barley under organic farming. Although Farm 1 performs conventional and organic farming, the studied system was focused only on 20 ha of organic farming fields (*"cradle to gate"*). Data collection included all the resources

needed as external inputs (e.g. buildings, fertilizers, soil tillage processes and irrigation) (Figure 4). Besides this, the years of production considered were only 2008, 2009 and 2010. The existence of two crops per year in each field, in most of the cases, made it necessary to allocate the area used for both crops according to the time of usage of the field (Appendix II). It is also important to keep in mind that, for all the inputs, databases from ecoinvent consider the cradle to gate life cycle. For example, for the processes of tillage, the production of machinery including the extraction of materials, diesel production and burn, usage and end of life of machinery are taken into account (Nemecek and Kägi, 2007). Any kind of transportation or commercialization was considered.

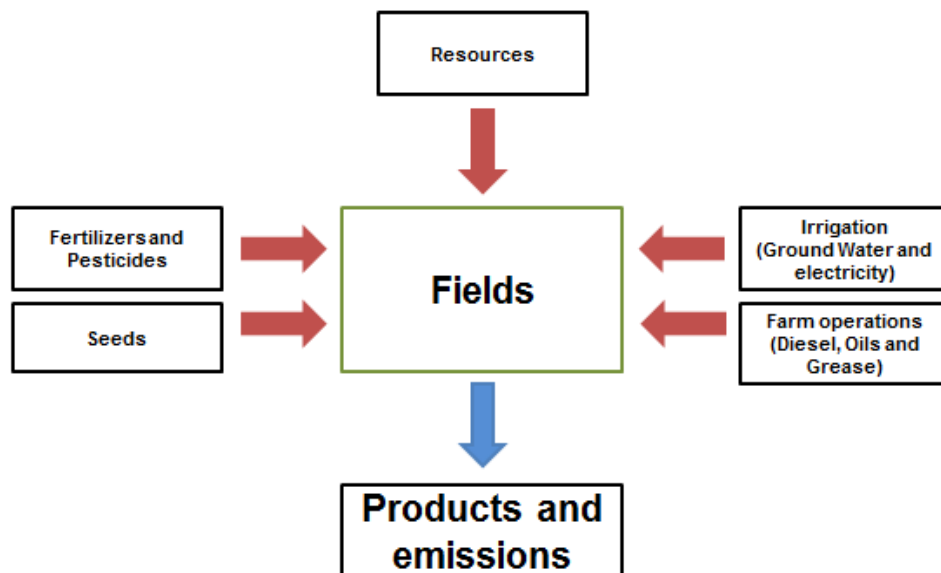


Figure 6 - System Boundaries of Farm 1.

According to Nemecek et al. (2011), agricultural systems are multifunctional and functional units belonging to three classes can be used to quantify their environmental performance. Each functional unit represents a purpose or function of the farm from different points of view (Nemecek et al., 2011):

- The land management function is measured per hectare and year ($\text{kg CO}_2 \text{ eq. ha}^{-1} \cdot \text{a}^{-1}$). The land occupation for agricultural production reveals a social

perspective of preserving this land for agriculture. The main goal is to decrease the impact per area and time unit;

- The financial function represents the main motivation for agricultural production, and, consequently, the farmer perspective. The unit is expressed per euro of return (kg CO₂ eq./€). The goal is to minimise the environmental impacts per currency unit and maximise eco-efficiency;
- The productive function is defined per kg of product (kg CO₂ eq./kg of product) and the goal is to minimise the environmental impacts per product unit. It represents mainly the perspective of consumers.

3.3. Data Collection

A detailed data collection is necessary to calculate a real approximation of the environmental impact of a product/service/process. SALCAcrop requires data such as region details, soil characteristics, erosion evidences, crop rotation scheme and species, tillage system and dates, fertilizers and pesticides inputs, type and amount of energy and water source, buildings' information, harvest yields and area. For that reason, two visits were performed to the Farm 1 in order to collect all the data needed. Although the visits were useful to understand all the system, some phone meetings were performed to fill in some missing data.

Table 7 summarises climate information and soil characteristics included as input data in SALCAcrop.

Table 7 - Region climate and soil characterists.

Mean Annual Precipitation	750 mm
Mean Annual Temperature	15 – 17.5 °C
Erosion evidences	The fields do not present any erosion evidence.
Organic Matter	1.62 %
Clay Content	33 %
Silt Content	43 %

Sand Content	24 %
pH	8.19

Fertilizers management can be crucial for the yields of the farms and are one of the greatest contributors for Global Warming Potential impact category. This farm uses both manure and other organic fertilizers. Table 8 summarises the rates of nutrients used in the software multiplied by the area used by each crop. Appendix I includes the composition and types of each fertilizer used.

Table 8 - Nutrient and Pesticides' inputs for each crop per hectare and year.

Type of Crop	Fertilizers and Pesticides' Inputs	2008	2009	2010
Tomato	Nitrogen	457.8 kg/ha	204.4 kg/ha	231.1 kg/ha
	Phosphorous	141.2 kg/ha	31.3 kg/ha	49.6 kg/ha
	Potassium	264.4 kg/ha	137.7 kg/ha	144.6 kg/ha
	Magnesium	24.90 kg/ha	12.5 kg/ha	20.0 kg/ha
	Sulphur	151.5 kg/ha	90.5 kg/ha	106.4 kg/ha
	Copper	4.00 kg/ha	2.50 kg/ha	2.00 kg/ha
	<i>Bacillus Thuringiensis</i>	0.128 kg/ha	0.032 kg/ha	0.064 kg/ha
	<i>Quassia amara</i> extract ^{a)}	-	-	9.00 kg/ha
	<i>Mimosa tenuiflora</i> extract ^{a)}	-	-	2.00 kg/ha
	Organic Matter	4607 kg/ha	1896 kg/ha	2368 kg/ha
	Aminoacids	2.06 kg/ha	2.06 kg/ha	2.06 kg/ha
Broccoli	Nitrogen	456.7 kg/ha	6.00 kg/ha	230.0 kg/ha
	Phosphorous	141.2 kg/ha	24.0 kg/ha	31.6 kg/ha
	Potassium	264.4 kg/ha	30.0 kg/ha	121.5 kg/ha
	Magnesium	24.90 kg/ha	10.0 kg/ha	12.5 kg/ha
	Sulphur	103.5 kg/ha	50.0 kg/ha	62.5 kg/ha
	<i>Bacillus Thuringiensis</i>	0.128 kg/ha	0.064 kg/ha	0.064 kg/ha
	Copper	4.00 kg/ha	3.00 kg/ha	0.50 kg/ha
	Calcium	70.0 kg/ha	-	-
	Sodium	3.50 kg/ha	-	-
	Organic Matter	4600 kg/ha	160 kg/ha	2361 kg/ha
Wheat	Nitrogen	272.2 kg/ha	249.3 kg/ha	-
	Phosphorous	139.9 kg/ha	31.63 kg/ha	-

	Potassium	197.2 kg/ha	154.5 kg/ha	-
	Magnesium	24.90 kg/ha	12.50 kg/ha	-
	Sulphur	103.5 kg/ha	62.50 kg/ha	-
	Calcium	70.00 kg/ha	-	-
	Sodium	3.50 kg/ha	-	-
	Organic Matter	2711 kg/ha	2361 kg/ha	
Barley	Nitrogen	272.2 kg/ha	249.3 kg/ha	-
	Phosphorous	139.9 kg/ha	31.63 kg/ha	-
	Potassium	197.2 kg/ha	154.5 kg/ha	-
	Magnesium	24.90 kg/ha	12.50 kg/ha	-
	Sulphur	103.5 kg/ha	62.50 kg/ha	-
	Calcium	70.00 kg/ha	-	-
	Sodium	3.50 kg/ha	-	-
	Organic Matter	2711 kg/ha	2361 kg/ha	-

a) Although the substance is used as a pesticide, legally, is counted as a fertilizer.

Most of the authors claim that diversification of crops and rotation management can give some essential nutrients and consistency to the soils. Farm 1 promotes variability of crops: tomato, broccoli, wheat and barley. Barley is used as break crop but also accounts as income when is produced. Besides this fact, double cropping systems (two crops per year) are performed. Table 9 show the crop rotation system adopted in 2008, 2009 and 2010 and the area of the fields. Table 10 presents the yields of each crop per year.

Table 9 - Crop rotation scheme of Farm 1.

Fields	2008	2009	2010	Area (ha)
1	Wheat/Barley	Tomato/Fallow	Fallow/Broccoli	5
2	Barley/Broccoli	Tomato/Broccoli	Tomato/Broccoli	5
3	Tomato/Broccoli	Wheat/Broccoli	Tomato/Broccoli	5
4	Tomato/Broccoli	Barley/Broccoli	Tomato/Broccoli	5

Table 10 - Yields per crop.

Type of Crop	Yield (ton/ha and year)		
	2008	2009	2010
Tomato	80	79	82
Broccoli	11	12	11
Wheat	5	5	-
Barley	5	5	-

Because of the existence of two crops in each field per year, it was necessary to allocate the area for each crop according to the cropping calendar. A cropping calendar divides the assessment time by periods that are counted from harvest to harvest (see Appendix II – crop rotation and area allocation). Besides that, also the storage building information was allocated per crop, because the existent building in the farm is used for the entire production, which means that the area has to be divided by crop. The building has 600 m² and the lifetime considered was 50 years (see Appendix III for the calculations of infrastructure allocations). Table 11 presents the results for allocated areas and infrastructures. In the following the calculation details are provided.

The allocated field area was calculated using the time allocated to one crop, in the field, divided by the total time of occupation in the cropping year multiplied by the area (5 ha) of the field.

$$\text{Allocated field area} = \frac{T_{\text{crop}}}{T_{\text{year}}} \times 5 \text{ ha} \quad (\text{Eq. 1})$$

T_{crop} - period from previous harvested and the harvest of the main crop.

T_{year} – total time of occupation in the cropping year.

The storage building was calculated dividing the allocated area for the total area occupied by organic cropping system (20 ha) multiplied by the total area occupied by the building (600 m²). This value was divided by the lifetime of the building (50 years).

$$\text{Allocated area of the Storage Building (m}^2\text{/year)} = \frac{\frac{\text{Allocated field area}}{20 \text{ ha}} \times 600 \text{ m}^2}{50 \text{ yrs}} \quad (\text{Eq. 2})$$

To perform irrigation processes, each field is equipped with a 120 m³ pump station and 2000 m of pipelines. Similarly, to the storage building, pump stations have a 50-year lifetime. On the other hand, for pipelines it was considered a lifetime of 20 years (see Appendix III for the calculations of the allocated equipment for irrigation). For the allocation of pipelines and pump stations, irrigation values were used. For tomato crop, it was used 850 m³ of water.ha⁻¹.yr⁻¹, while for broccoli it was used 750 m³ of water.ha⁻¹.yr⁻¹. Water used per crop is divided the total amount used for the three years in the farm. That result is multiplied by the total length of the pipelines and divided by lifetime (20 years). The calculation for pump stations volume used 120 m³ of volume and 50-year lifetime.

$$\text{Allocated length of Pipelines (m/year)} = \frac{\frac{m_{\text{crop}}^3}{m_{\text{farm}}^3} \times 2000 \text{ m}}{20} \quad (\text{Eq. 3})$$

$$\text{Allocated volume of the Pump station (m}^3\text{/year)} = \frac{\frac{m_{\text{crop}}^3}{m_{\text{farm}}^3} \times 120 \text{ m}^3}{50} \quad (\text{Eq. 4})$$

m³_{crop} – water used per crop.

m³_{farm} – water used for the whole farm for the three year.

Table 11 - Allocated field area, storage building, pipelines and pump stations.

Type of crop	Type of infrastructure	2008	2009	2010
Barley	Allocated Area (ha)	5.92	2.92	-
	Storage Building (m ²)	3.55	1.75	-
	Pipelines (m)	-	-	-
	Pump Stations (m ³)	-	-	-
Wheat	Allocated Area (ha)	2.00	3.21	-
	Storage Building (m ²)	1.20	1.93	-
	Pipelines (m)	-	-	-
	Pump Stations (m ³)	-	-	-
Tomato	Allocated Area (ha)	7.40	8.33	10.0
	Storage Building (m ²)	4.44	5.00	6.00
	Pipelines (m)	12.64	12.64	18.96
	Pump Stations (m ³)	0.30	0.30	0.45
Brocoli	Allocated Area (ha)	4.69	5.54	10.0
	Storage Building (m ²)	2.81	3.32	6.00
	Pipelines (m)	16.74	16.74	22.32
	Pump Stations (m ³)	0.39	0.39	0.52

Tillage processes and irrigation values are also important for GWP. Tillage processes consider machinery and diesel used. On the other hand, irrigation takes into account electricity used. Besides this, dates of tillage and sowing processes are taken into account for occupation arable land. Table 12 identifies the soil tillage processes, sowing or planting and harvest dates for each crop.

Table 12 – Processes and dates of soil tillage processes, sowing/planting and harvest for each crop.

Type of Crop	Sowing/ planting	Harvest	Soil Tillage
Tomato	April	August	Harrowing, Chisel, Ploughing and seedbed preparation ^{a)}
Broccoli	August/September	December/ January	Harrowing, Chisel and Ploughing ^{a)}
Barley	January	July	
Wheat	November	July	

a) Soil tillage processes occur between 1 month and a half and 1 month before sowing/planting

3.4. No-tillage Scenario

This was the scenario considered for this case study. To run this scenario, the tillage processes were excluded from the model, which means that tillage effect was removed from the inventory in order to build the scenario. However, some assumptions were needed to consider in order allowing this case.

Productivity yields, fertilization rates and irrigation demands were kept the same as the original inventory. However, it is important to refer that the authors state that no-tillage practices influence the three parameters.

3.5. Carbon Sequestration Scenario

As previously mentioned some reviewed studies state that no-tillage contributes for carbon sequestration. This study investigates this assumption by assessing the effect of carbon sequestration in the no-tillage scenario. This scenario was carried out by using the collected data from literature regarding meta-analyses performed for carbon sequestration rates for several crops, different soil management and observed soil depths. The main goal of the meta-analyses was to conclude about the influence of converting from conventional tillage to no-tillage management. Although the studies presented show results for four meta-analyses, West and Post (2002) was not included in the study because the soil depth influences deeply the results. Once the soil mean depth, measured in the studies used in the meta-analysis, was to 35 cm (only top soil), the resulting carbon sequestration rate is very large compared to the others.

This thesis considers two scenarios obtained from the meta-analysis presented on chapter 2. Scenario 1 was built based on the value presented by Angers and Eriksen-Hamel (2008) equal to $0.31 \text{ ton C.ha}^{-1}.\text{yr}^{-1}$. Scenario 2 was based on the value presented by Luo et al. (2010) that is $-0.15 \text{ ton C.ha}^{-1}.\text{yr}^{-1}$. A conversion from $\text{ton C.ha}^{-1}.\text{yr}^{-1}$ to $\text{ton CO}_2.\text{ha}^{-1}.\text{yr}^{-1}$ was needed to include the rates in the crop production (Table 13).

Table 13 - Conversion of Carbon Sequestration Rates, from $\text{ton C.ha}^{-1}.\text{yr}^{-1}$ to $\text{ton CO}_2.\text{ha}^{-1}.\text{yr}^{-1}$.

	Rate of C sequestration ($\text{ton C.ha}^{-1}.\text{yr}^{-1}$)	Rate of C sequestration ($\text{ton CO}_2.\text{ha}^{-1}.\text{yr}^{-1}$)
Scenario 1	0,31	1,14
Scenario 2	-0,15	-0,55

Having two crops per year, made necessary some allocations of this rates per crop in order to include it in the results. Equation 5 was used for the allocation. After allocation the weighted mean was calculated by Equation 6:

$$Scenario_i \text{ for crop } y = C \text{ sequestration rate}_i \times Allocated \text{ area}_{crop \ y, year \ z} \quad (Eq. 5)$$

$$C \text{ sequestration rate}_{crop \ (3 \ years)} = \frac{\sum Scenario_i \text{ for crop } y \times Allocated \ Area_{crop \ y, year \ z}}{\sum Allocated \ Area_{crop \ y, year \ z}} = \text{ton } CO_2 \cdot ha^{-1} \cdot yr^{-1} \quad (Eq.6)$$

At the end the carbon sequestration rate calculated per crop for the three years, was added to the no-tillage results per crop.

4. Results and Discussion

This chapter presents and discusses the carbon footprint results obtained in the SimaPro software by using the SALCA method earlier described in Chapter 2. The assesment was performed for the current management practices at the farm and for the no-tillage scenario. The carbon sequestration rates used to calculate the carbon footprint reported to the land management functional unit (expressed in $\text{ton CO}_2\cdot\text{ha}^{-1}\cdot\text{a}^{-1}$) were retrieved from the literature, for the impact category (GWP over 100-year horizon) and for the no-tillage scenario.

Tables 14-16 present the results for the carbon footprint for each crop grown under current management practices and for the no-tillage scenario. The carbon footprint results are reported per mass of product (kg of product harvested), area (hectare of land used) and economic profits (€ of profit value).

The no-tillage scenario was built by removing the tillage processes from the life-cycle inventory. The tillage processes include essentially the fuel and machinery production and use during the soil management. More specifically it considers: diesel production, diesel burn, machinery construction (including material extraction and end of life scenarios) and usage (maintenance inputs such oil and grease). The carbon footprint results present lower value for the no-tillage scenario by comparison to the current management practices.

Table 14 shows the results reported to mass of product. Wheat was the crop with the largest carbon footprint for both 2008 and 2009 and tomato was the crop with lowest carbon footprint for all years considered. It is also visible that the carbon footprint decreases along the years of all crops. In addition, the GHG emissions for broccoli drastically decrease in 2009. Results for tomato might seem smaller when compared to the other crops. However, a study conducted in Spain presented results in the same order of magnitude (Muñoz et al., 2007).

The grain crops (barley and wheat) show to have lower yields. It is then clear that the carbon footprint for these crops is larger than for vegetable crops (tomato and broccoli). It is also possible to conclude that the production for wheat is lower than for barley leading to the larger footprint for this later crop. On the other hand, tomato had

the largest yield and that explains its lowest carbon dioxide emissions. The decreasing values, along the years, for all the crops are due to the decrease in the fertilizer inputs. The lowest value for broccoli, in 2009, is explained by the absence of a manure input in that year. When there is not enough manure supplied for the production, other organic fertilizers are used instead. The amount of nitrogen in these products is much lower comparison to manure.

Table 14 - Carbon Footprint of each crop expressed in the productive function for the current management practices at the farm and no-tillage scenario.

Type of Crop	Type of Management	Carbon footprint (ton CO ₂ eq./ton of product harvested)		
		Year 2008	Year 2009	Year 2010
Barley	Current Management	0.565	0.526	a)
	No-tillage	0.487	0.447	a)
Wheat	Current Management	0.590	0.535	a)
	No-tillage	0.508	0.455	a)
Tomato	Current Management	0.0558	0.0361	0.0374
	No-tillage	0.0507	0.031	0.0324
Broccoli	Current Management	0.401	0.116	0.282
	No-tillage	0.364	0.0810	0.243

a) Barley and wheat were not produced in 2010.

Table 15 presents the results for carbon footprint per land use unit for the current management and for the no-tillage scenario. Broccoli shows to have the largest carbon footprint for the three years. On the other hand, wheat is the crop with lowest carbon footprint for 2008 and 2009. In addition, for grain crops, the results increased from 2008 to 2009, while for vegetable crops decreased. From 2009 to 2010, the carbon footprint of broccoli and tomato slightly increases. The results for carbon footprint per area use the allocated area (see chapter 4 for further details of allocated area) i.e. the total impact is divided by the allocated area.

For barley, in 2009, the area used declined. Consequently, carbon footprint increased. In case of wheat, from 2008 to 2009, area used increased and for that reason, the amount of fertilizer and tillage practices applied increased. That naturally leads to an

increasing of carbon footprint. For broccoli and tomato, as it was said, fertilizer rates decreased from 2008 to 2009. In terms of area occupied by these two crops, it increased. The combination of these two factors meant a drastically decreasing value for carbon footprint in 2009. In 2010, fertilizer rates increased but the area occupied also increased. However, the balance between increasing values led to a small increase of the impact for vegetable crops in 2010.

Table 15 - Carbon Footprint of each crop expressed in the land management function for the current management and for no-tillage scenario.

Type of Crop	Type of Management	Carbon footprint (ton CO ₂ eq./ha of land used/year)		
		Year 2008	Year 2009	Year 2010
Barley	Current Management	3.82	4.50	a)
	No-tillage	3.29	3.83	a)
Wheat	Current Management	2.95	4.02	a)
	No-tillage	2.54	3.42	a)
Tomato	Current Management	6.04	3.43	4.61
	No-tillage	5.49	2.93	3.99
Broccoli	Current Management	14.10	3.84	8.40
	No-tillage	12.80	2.69	5.14

a) Barley and wheat were not produced in 2010.

Table 16 presents the carbon footprint per unit of profit for the farm for the current management practices and for the no-tillage scenario. Results were calculated based on a weighted mean divided by the profit value of the considered year (Eq. 7).

$$\text{Carbon footprint per year} = \frac{\sum \text{GWP result per area unit}_{\text{crop y, year z}} \times \text{Allocated Area}_{\text{crop y, year z}}}{\text{Profit Value}} = \text{kg CO}_2 \text{ eq. } \text{€}^{-1} \text{ of profit value} \quad (\text{Eq. 7})$$

For both management practices, the values for the carbon footprint are larger for 2008 and by contrast lower for 2009. This fact can be explained by the amount of fertilizers applied to the soil. In 2008, the rate of fertilizers applied was larger than any other

year. On the other hand, in 2009 there had no manure input for the broccoli crop resulting in a very low footprint value.

Table 16 - Carbon Footprint of the farm expressed per unit of profit for the whole farm for current management and no-tillage scenario with the reduction percentage of the carbon footprint.

Type of Management	Carbon footprint (kg CO ₂ eq./€)		
	Year 2008	Year 2009	Year 2010
Current Management	3.48	1.58	3.38
No-tillage Scenario	3.13	1.28	2.37
Percentage of reduction from the Current Management to No-tillage Scenario	-10 %	-19 %	-30 %

Figures 7 and 8 show the results, respectively, for the productive and the area functional units per year. The figures also show the carbon footprint reduction (%) obtained by using the no-tillage scenario in comparison to the current management practices. Equations 8 and 9 were used to calculate, respectively, the footprint per mass of product harvested and the footprint per area of land used.

$$\text{Carbon footprint per year} = \frac{\sum \text{GWP result per productivity unit}_{\text{crop y, year z}} \times \text{Production}_{\text{crop y, year z}}}{\sum \text{Production}_{\text{crop y, year z}}} =$$

ton CO₂ eq. ton⁻¹ of product harvested (Eq. 8)

$$\text{Carbon footprint per year} = \frac{\sum \text{GWP result per area unit}_{\text{crop y, year z}} \times \text{Allocated Area}_{\text{crop y, year z}}}{\sum \text{Allocated Area}_{\text{crop y, year z}}} =$$

ton CO₂ eq. ha⁻¹ of land used. a⁻¹ (Eq. 9)

Analysing both figures it is possible to conclude that no-tillage practices can reduce the emissions of the production due to the reduction in the machinery usage.

For both functional units the year of 2009 was the one presenting the lowest footprint. On the other hand, 2008 presents the larger footprint. Reductions in 2008 and 2009 were identical (-10% and -19%) for both functional units. In 2010, the reduction in the carbon footprint was larger for the area functional unit (-30%) compared to the productive functional unit (-14%).



Figure 7 - Global warming potential for the productive unit per year, comparing the current management with no-tillage scenario.

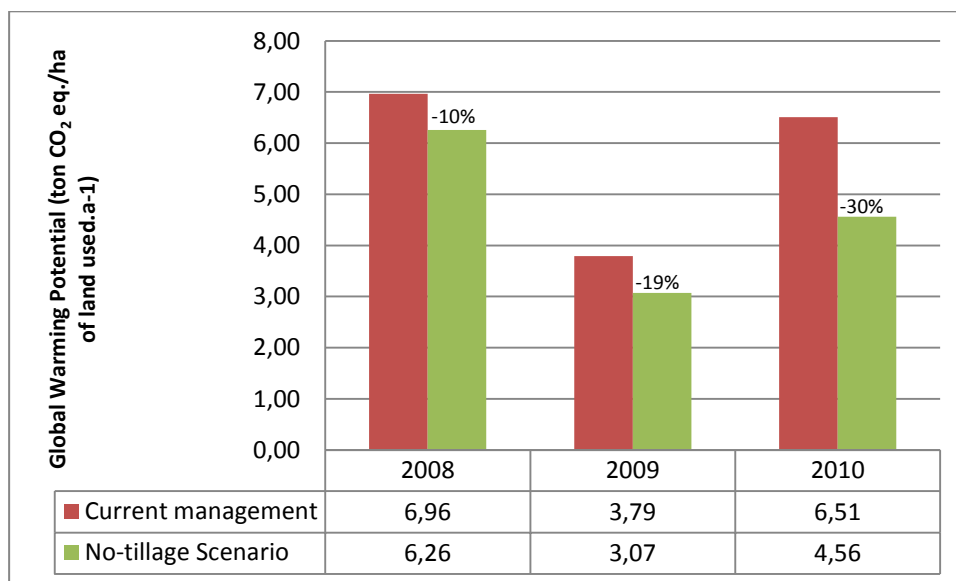


Figure 8 - Global warming potential for the land management unit, comparing the current management with no-tillage scenario.

Figures 9 and 10 present the results, respectively, for scenario 1 and scenario 2, already explained in the last section of chapter 3.

It is visible the influence of carbon sequestration in the carbon footprint results. The resulting values for the carbon footprint vary for all crops when reported to the no-tillage scenario (Figure 9). The maximum reduction is for wheat (-37 % when reported

to the no-tillage scenario). The larger increase is also for wheat (+18 % reported to the no-tillage scenario).

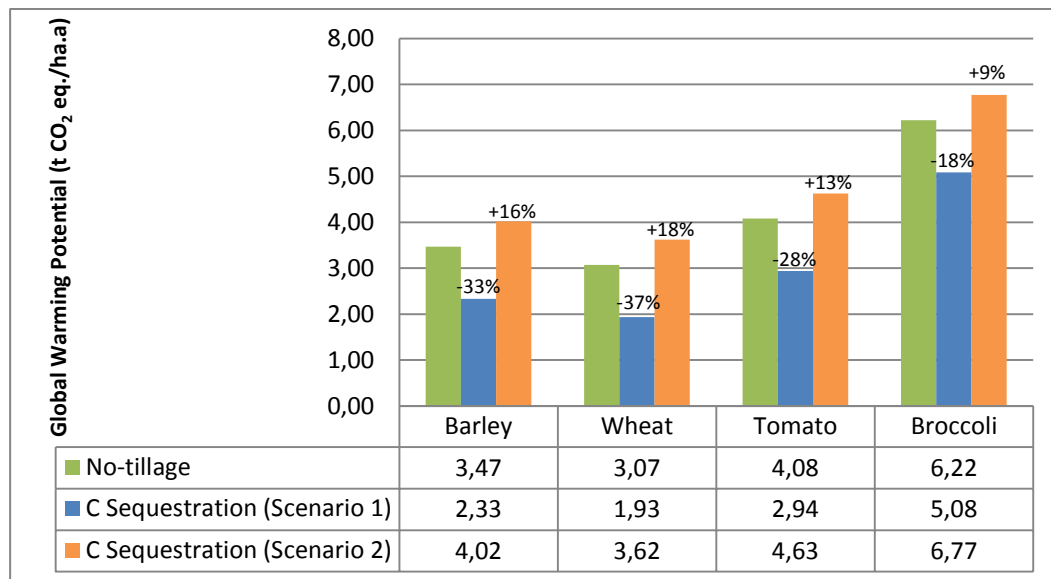


Figure 9 – Results of the influence of carbon sequestration rates in the no-tillage scenario per each crop, per area.

When the whole farm is analysed (Figure 10), the maximum reduction is for 2009 (-19 % reported to the no-tillage) and the minimum reduction in 2008 (-9 % reported to the no-tillage). It is visible here the variation in the carbon footprint results associated to the consideration of the carbon sequestration rates retrieved from the meta-analyses available in the related literature.

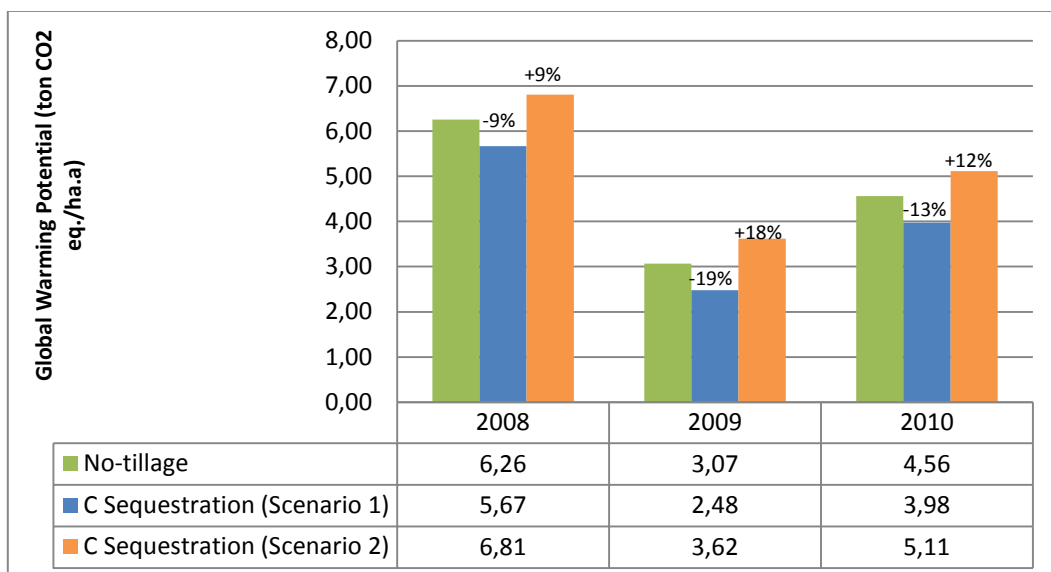


Figure 10 - Results of the influence of carbon sequestration rates in the no-tillage scenario for the whole farm, per area.

5. Conclusions and Future Work

Agriculture is one of the main contributors to climate change and one of the most important productive sectors in the world. For that reason, it is important to assess its environmental impacts. In Portugal, the agricultural sector plays an important role in the economic and social areas.

This thesis focus on the productive process from one farm located in central region of Portugal and assesses the Global Warming Potential over 100-years horizon for the organic products from the farm. The data collected includes the fertilization inputs, tillage and sowing processes, irrigation rates and information about the infrastructure. The organic products in focus are vegetables products (as tomato and broccoli) and grain products (as barley and wheat).

In terms of productive unit (where the carbon footprint is expressed in ton of harvested product), the tomato crop has the lowest carbon footprint by contrast to wheat that shows to have the largest. For the time scale studied tomato crop presented values between 0.0361 and 0.0558 ton CO₂.ha⁻¹.yr⁻¹, for current management practices. For wheat, values are between 10 and 12 times larger. These results are mainly due to the crop productions. The production for tomato is the largest, while production for wheat is the lowest. It is also possible to conclude that the carbon footprint, for all the crops decreases along the years. This is the result of a reduction on the use of fertilizers.

Looking into the land management function (where the carbon footprint is expressed in ton CO₂ eq. ha⁻¹ of land used.year⁻¹), the grain crops (wheat and barley) footprints increased from 2008 to 2009 while for vegetable crops (tomato and broccoli) the carbon footprint decreased. However, broccoli was definitely the crop with largest carbon footprint, in 2008. The largest impact for wheat and barley was in 2009 (respectively, 4.02 and 4.50 ton CO₂ eq. ha⁻¹ of land used.year⁻¹). Low allocated area and large inputs of fertilizer in 2008, promoted the large impact for vegetable crops.

When the global results for the whole farm is of concern it is possible to conclude that for the three functional units (profit value, production and area) the year presenting the lowest carbon footprint is 2009 while the largest is 2008. In terms of profit

functional unit, current management practices have an impact of 0.174 kg CO₂ eq./€, in 2008, while in 2009 this value decreases to 0.079 kg CO₂ eq./€.

When the results obtained for the carbon footprint for the no-tillage scenario are analysed it is clear that the carbon footprint decreases due to the absence of tillage processes. Decreasing values for the three functional units varied from -10 % to -30 %. The literature review concerning carbon sequestration shows that conversion from conventional tillage (current management in the farm) to no-tillage may change significantly the carbon footprint. However, the lack of agreement and the missing standard patterns to study carbon sequestration, leads to a large range of results. This fact, when translated to carbon footprint, presents a large variation in the results. From this it is possible to conclude that although it is possible to include carbon sequestration effects in life cycle assessment the uncertainty associated to the carbon footprint results is very large (from + 18% to – 37 % when each crop is analysed and from + 18 % to – 19 % for the whole farm results).

This study leads to the conclusion that, although it is possible to include carbon sequestration effects in life cycle assessment, variations in results are very large. The uncertainty generated in the field results and the lack of agreement in carbon sequestration topic is reported to the meta-analysis and, consequently, to the calculated results.

Some limitations were identified during this work. One is related to the incorporation of carbon sequestration in life cycle results. The lack of a standard pattern that can be used to evaluate carbon sequestration does not help in draw a conclusion about the influence of different managements.

Opportunities to extend the work here done are possible. One is, for example, the extension of the studies for the tillage scenario. Here more studies and differences on yields, irrigation rates and fertilizer can be included. Also, the real effects of different tillage managements in carbon stock changes should be evaluated by using field experiment. This can be achieved by sampling the entire soil profile.

The study of crops influence on carbon sequestration rates considering specific species and rotation, should be analyse and eventually, developed in the field. For this to occur in the way that a comparison of crops results is possible the management practices have to be similar. This can be extended to other crops than grain and leguminous. It is

clear that vegetables crops do not present the same potential as the most crops studied, however, some field experiments should be done.

In order to study the effects of fertilizers, standard methods should be developed so the same amount and type of fertilizer can be inputted in the soil and more accurate conclusions can be attained. At the end, the real effects of climate and soil structure are also a controversial issue that should be further investigated. This could be done by applying alternative crop management practices in different regions to promote the variety on climate conditions and soil structure.

A recommendation for the farm would be to increase organic matter input so the quality of the soil can improve and the necessity of the tillage decreases.

References

- ABU-ZAHRA, T. R. & TAHBOUB, A. B. 2008. Effect of Organic Matter Sources on Chemical Properties of the Soil and Yield of Strawberry under Organic Farming Conditions. *World Applied Sciences Journal*, 5 (3), 383-388.
- ALVAREZ, R. 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. *Soil Use and Management*, 21, 38-52.
- AMBIENTE, A. P. D. *Atlas do Ambiente*.
- ANGERS, D. A., BOLINDER, M. A., CARTER, M. R., GREGORICH, E. G., DRURY, C. F., LIANG, B. C., VORONEY, R. P., SIMARD, R. R., DONALD, R. G., BEYAERT, R. P. & MARTEL, J. 1997. Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. *Soil and Tillage Research*, 41, 191-201.
- ANGERS, D. A. & ERIKSEN-HAMEL, N. S. 2008. Full-Inversion Tillage and Organic Carbon Distribution in Soil Profiles: A Meta-Analysis. *Soil Science Society of America Journal*, 72, 1370-1374.
- BAKER, J. M., OCHSNER, T. E., VENTEREA, R. T. & GRIFFIS, T. J. 2007. Tillage and soil carbon sequestration - What do we really know? *Agriculture, Ecosystems & Environment*, 118, 1-5.
- BARROW, C. J. 2012. Biochar: Potential for countering land degradation and for improving agriculture. *Applied Geography*, 34, 21-28.
- BOLINDER, M. A., JANZEN, H. H., GREGORICH, E. G., ANGERS, D. A. & VANDENBYGAART, A. J. 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agriculture, Ecosystems & Environment*, 118, 29-42.
- BRANDÃO, M., MILÀ I CANALS, L. & CLIFT, R. 2011. Soil organic carbon changes in the cultivation of energy crops: Implications for GHG balances and soil quality for use in LCA. *Biomass and Bioenergy*, 35, 2323-2336.
- CARTER, M. R. 2005. Long-term tillage effects on cool-season soybean in rotation with barley, soil properties and carbon and nitrogen storage for fine sandy loams in the humid climate of Atlantic Canada. *Soil and Tillage Research*, 81, 109-120.
- DEEN, W. & KATAKI, P. K. 2003. Carbon sequestration in a long-term conventional versus conservation tillage experiment. *Soil and Tillage Research*, 74, 143-150.
- DOLAN, M. S., CLAPP, C. E., ALLMARAS, R. R., BAKER, J. M. & MOLINA, J. A. E. 2006. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. *Soil and Tillage Research*, 89, 221-231.
- ESA. 2000. *Carbon Sequestration in Soils* [Online].
- FAO. 2007. *In climate Change Mitigation* [Online]. Available: <http://www.fao.org/es/esa/pesal/AgRole2.html> [Accessed 23rd of June 2012].
- FREIBAUER, A., ROUNSEVELL, M. D. A., SMITH, P. & VERHAGEN, J. 2004. Carbon sequestration in the agricultural soils of Europe. *Geoderma*, 122, 1-23.
- GAISER, T., ABDEL-RAZEK, M. & BAKARA, H. 2009. Modeling carbon sequestration under zero-tillage at the regional scale. II. The influence of crop rotation and soil type. *Ecological Modelling*, 220, 3372-3379.
- GLOBAL, A. P. 2011. Portugal - Perfil.
- GONG, W., YAN, X., WANG, J., HU, T. & GONG, Y. 2009. Long-term manure and fertilizer effects on soil organic matter fractions and microbes under a wheat-maize cropping system in northern China. *Geoderma*, 149, 318-324.
- HATI, K. M., SWARUP, A., MISHRA, B., MANNA, M. C., WANJARI, R. H., MANDAL, K. G. & MISRA, A. K. 2008. Impact of long-term application of fertilizer, manure and lime under

- intensive cropping on physical properties and organic carbon content of an Alfisol. *Geoderma*, 148, 173-179.
- HERNANZ, J. L., SÁCHEZ-GIRÓN, V. & NAVARRETE, L. 2009. Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. *Agriculture, Ecosystems & Environment*, 133, 114-122.
- HIDRAULICA, I. D. D. R. E. 2010. Definição e caracterização das manchas territoriais para efeitos de aplicação do Leader +.
- IPCC 2007a. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*.
- IPCC 2007b. Summary for Policemakers. In: BASIS, C. C. T. P. S. (ed.) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Assessement Report of Intergovernmental Panel on Climate Change: Intergovernmental Panel on Climate Change.
- JARECKI, M. K. & LAL, R. 2003. Crop Management and Soil Carbon Sequestration. *Critical Reviews in Plant Sciences*, 22(5), 471-502.
- KUKAL, S. S., REHANA, R. & BENBI, D. K. 2009. Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice-wheat and maize-wheat systems. *Soil and Tillage Research*, 102, 87-92.
- LAL, R. 2004. Soil carbon sequestration to mitigate climate change. *Geoderma*, 123, 1-22.
- LOU, Y., WANG, J. & LIANG, W. 2011. Impacts of 22-year organic and inorganic N managements on soil organic C fractions in a maize field, northeast China. *CATENA*, 87, 386-390.
- LUO, Z., WANG, E. & SUN, O. J. 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. *Agriculture, Ecosystems & Environment*, 139, 224-231.
- MACIEL, H., PEREIRA, T. C., SEABRA, T., TORRES, P., CANAVEIRA, P. & MOURÃO, I. 2012. Portuguese National Inventory Report on Greenhouse Gases, 1990-2010. In: AGENCY, P. E. (ed.).
- MAHDI M. AL-KAISI, X. Y. 2005. Tillage and Crop Residue effects and Soil Carbon and Carbon Dioxide Emission in corn-soybean rotations. *Journal of Environmental Quality*, 34, 437-445.
- MALÇA, J. & FREIRE, F. 2012. Adressing Land use Change and uncertainty in the life-cycle assessment of wheat-based bioethanol. *Energy*, in Press.
- MANDLEBAUM, S. & NRIAGU, J. 2011. Carbon Sequestration and Agriculture. In: EDITOR-IN-CHIEF: JEROME, O. N. (ed.) *Encyclopedia of Environmental Health*. Burlington: Elsevier.
- MAZZONCINI, M., SAPKOTA, T. B., BÀRBERI, P., ANTICHI, D. & RISALITI, R. 2011. Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. *Soil and Tillage Research*, 114, 165-174.
- MCCONKEY, B. G., LIANG, B. C., CAMPBELL, C. A., CURTIN, D., MOULIN, A., BRANDT, S. A. & LAFOND, G. P. 2003. Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils. *Soil and Tillage Research*, 74, 81-90.
- MUÑOZ, P., ANTÓN, A., NUÑEZ, M., PARANJPE, A., ARIÑO, J., CASTELLS, X., MONTERO, J. I. & RIERADEVALL, J. 2007. Comparing the Environmental Impacts of Greenhouse versus Open-field tomato production in the Mediterranean Region. *International Symposium on High Technology for Greenhouse System Management: Greensys2007*. ISHS Acta Horticulturae.
- NEMECEK, T., DUBOIS, D., HUGUENIN-ELIE, O. & GAILLARD, G. 2011. Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. *Agricultural Systems*, 104, 217-232.
- NEMECEK, T. & KÄGI, T. 2007. Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent v2.0 No.15. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.
-

- NEMECEK, T., KNUCHEL, R. F., ALIG, M. & GAILLARD, G. The advantages of generic LCA tools for agriculture: examples SALCAcrop and SALCAfarm. 7th Int. conference on life cycle assessment in the agri-food sector, 2010. 433-438.
- NIGGLI, U., FLIESSBACH, A., HEPPELY, P. & SCIALABBA, N. E. 2009. Low Greenhouse Gas Agriculture: Mitigation and Adaptation Potential of Sustainable Farming Systems. *FAO*, 2.
- NIGGLI, U. & SCIALABBA, N. E. 2011. Organic Agriculture and Climate Change Mitigation: A Report of the Round Table on Organic Agriculture and Climate Change. *FAO*.
- OLSON, K. R., LANG, J. M. & EBELHAR, S. A. 2005. Soil organic carbon changes after 12 years of no-tillage and tillage of Grantsburg soils in southern Illinois. *Soil and Tillage Research*, 81, 217-225.
- PRÉ-CONSULTANTS. 2012. *About SimaPro* [Online]. Available: <http://www.pre-sustainability.com/content/simapro-lca-software> [Accessed 30th of April 2012].
- PURAKAYASTHA, T. J., RUDRAPPA, L., SINGH, D., SWARUP, A. & BHADRARAY, S. 2008. Long-term impact of fertilizers on soil organic carbon pools and sequestration rates in maize-wheat-cowpea cropping system. *Geoderma*, 144, 370-378.
- ROBERTS, K. G., GLOY, B. A., JOSEPH, S., SCOTT, N. R. & LEHMANN, J. 2010. Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. *Environmental Science Technology*, 44, 827-833.
- ROGNER, H.-H., ZHOU, D., R.BRANDLEY, P., CRABBÉ, EDENHOFER, HARE, B., KUJIPERS, L. & YAMAGUCHI, M. 2007. Introduction. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*.
- SAINJU, U. M., SENWO, Z. N., NYAKATAWA, E. Z., TAZISONG, I. A. & REDDY, K. C. 2008. Soil carbon and nitrogen sequestration as affected by long-term tillage, cropping systems, and nitrogen fertilizer sources. *Agriculture, Ecosystems & Environment*, 127, 234-240.
- SIX, J., ELLIOTT, E. T. & PAUSTIAN, K. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, 32, 2099-2103.
- SIX, J., OGLE, S. M., BREIDT, F. J., CONANT, R. T., MOSIER, A. R. & PAUSTIAN, K. 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long-term. 10, 155-160.
- SMITH, P. 2004. Carbon sequestration in croplands: the potential in Europe and the global context. *European Journal of Agronomy*, 20, 229-236.
- SMITH, P., MARTINO, D., CAI, Z., GWARY, D., JANZEN, H., KUMAR, P., MCCARL, B., OGLE, S., O'MARA, F., RICE, C., SCHOLLES, B. & SIROTENKO, O. 2007. Agriculture. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*.
- SOLIBAM. 2010a. *Presentation Brochure* [Online]. Available: <http://www.solibam.eu/modules/wfdownloads/viewcat.php?cid=5> [Accessed 28th of February 2012].
- SOLIBAM. 2010b. *WP8 - Environmental, economic and social sustainability assessment* [Online]. Available: <http://www.solibam.eu/modules/content/content.php?page=wp8> [Accessed 28th of February 2012].
- SOMBRERO, A. & DE BENITO, A. 2010. Carbon accumulation in soil. Ten-year study of conservation tillage and crop rotation in a semi-arid area of Castile-Leon, Spain. *Soil and Tillage Research*, 107, 64-70.
- USSIRI, D. A. N. & LAL, R. 2009. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. *Soil and Tillage Research*, 104, 39-47.

- VACCARI, F. P., BARONTI, S., LUGATO, E., GENESIO, L., CASTALDI, S., FORNASIER, F. & MIGLIETTA, F. 2011. Biochar as a strategy to sequester carbon and increase yield in durum wheat. *European Journal of Agronomy*, 34, 231–238.
- VIJAYAVENKATARAMAN, S., INIYAN, S. & GOIC, R. 2012. A review of climate change, mitigation and adaptation. *Renewable and Sustainable Energy Reviews*, 16, 878-897.
- WEST, T. O. & POST, W. M. 2002. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis. *Soil Science Society of America Journal*, 66, 1930–1946.
- ZHAI, L.-M., LIU, H.-B., ZHANG, J.-Z., HUANG, J. & WANG, B.-R. 2011. Long-Term Application of Organic Manure and Mineral Fertilizer on N₂O and CO₂ Emissions in a Red Soil from Cultivated Maize-Wheat Rotation in China. *Agricultural Sciences in China*, 10, 1748-1757.
- ZHANG, Y., LI, Y., JIANG, L. & TIAN, C. 2011. Potential of Perennial Crop on Environmental Sustainability of Agriculture. *Procedia Environmental Sciences*, 10, 1141-1147.
- ZINN, Y. L., LAL, R. & RESCK, D. V. S. 2005. Texture and organic carbon relations described by a profile pedotransfer function for Brazilian Cerrado soils. *Geoderma*, 127, 168-173.

APPENDIX

Appendix I – Fertilizer types and compositions.

Table AI.1- Fertilizer input rates.

Type of Crop	Type of fertilizer	Application rates		
		2008	2009	2010
Tomato	Horse Manure	18.0 ton/ha	8.00 ton/ha	10.0 ton/ha
	Patent Kali	400 kg/ha	250 kg/ha	400 kg/ha
	Blen-fer	700 kg/ha	a)	a)
	Avant Natur	20.0 L/ha	20.0 L/ha	20.0 L/ha
	Biofert	a)	550 kg/ha	a)
	L.O.M. ^{b)}	a)	a)	250 kg/ha
Broccoli	Horse Manure	18.0 ton/ha	a)	10.0 ton/ha
	Patent Kali	400 kg/ha	200 kg/ha	250 kg/ha
	Blen-fer	700 kg/ha	a)	a)
	Biofert	a)	a)	a)
	L.O.M. ^{d)}	a)	200 kg/ha	a)
Wheat ^{c)}	Horse Manure	10.0 ton/ha	10.0 ton/ha	-
	Patent Kali	400 kg/ha	250 kg/ha	-
	Blen-fer	700 kg/ha	a)	-
	Biofert	a)	550 kg/ha	-
Barley ^{c)}	Horse Manure	10.0 ton/ha	10.0 ton/ha	-
	Patent Kali	400 kg/ha	250 kg/ha	-
	Blen-fer	700 kg/ha	a)	-
	Biofert	a)	550 kg/ha	-

a) Not applied.

b) Liquid Organic Matter.

c) Wheat and barley were not produced in 2010.

Table AI.2 - Fertilizer's composition

Fertilizer	N	P	K	Mg	S	Ca	Na	a.a.^{b)}	OM^{c)}
Horse Manure ^{a)}	2.30 %	163.43 ppm	8400 ppm	-	-	-	-	-	23.61%
Patent Kali	-	12.0 %	15.0 %	5.00 %	25.0 %	-	-	-	-
Blen-fer	6.10 %	12.9 %	7.60 %	0.70 %	0.50 %	10.0 %	0.50 %	-	50.0 %
Avant Natur	5.50 %	-	-	-	-	-	-	10.3 %	37.3 %
Biofert	3.50 %	-	6.00 %	-	-	-	-	-	-
L.O.M.	-	-	-	-	-	-	-	-	80.0 %

a) SALCA's model uses cattle manure and according to Abu-Zahra and Tahboub (2008), composition of horse and cattle manure are similar (Abu-Zahra and Tahboub, 2008).

b) Amino acids.

c) Organic Matter.

Appendix II – Crop Rotation and allocation area.

Tables AII.1 – Crop rotation along the years.

Fields	Jul-07	Ago-07	Set-07	Oct 07	Nov-07	Dec-07	Jan-08	Fev-08	Mar-08	Abr-08	May 08	Jun-08	Jul-08	Ago-08	Sept-08	Oct 08	Nov-08	Dec 08
1					Wheat	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat					
							Barley	Barley	Barley	Barley	Barley	Barley	Barley					
2							Barley	Barley	Barley	Barley	Barley	Barley	Barley		Broccoli	Broccoli	Broccoli	Broccoli
3										Tomato	Tomato	Tomato	Tomato	Tomato	Broccoli	Broccoli	Broccoli	Wheat
4										Tomato	Tomato	Tomato	Tomato	Tomato	Broccoli	Broccoli	Broccoli	Broccoli

Fields	Dec 08	Jan-09	Fev-09	Mar-09	Abr-09	May-09	Jun-09	Jul-09	Ago-09	Sept-09	Oct-09	Nov-09	Dec-09
1					Tomato	Tomato	Tomato	Tomato	Tomato				
2	Broccoli				Tomato	Tomato	Tomato	Tomato	Tomato	Broccoli	Broccoli	Broccoli	Broccoli
3	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat		Broccoli	Broccoli	Broccoli	Broccoli
4	Broccoli	Barley	Barley	Barley	Barley	Barley	Barley	Barley		Broccoli	Broccoli	Broccoli	Broccoli

Fields	Dec-09	Jan-10	Fev-10	Mar-10	Abr-10	May-10	Jun-10	Jul-10	Ago-10	Sept-10	Oct-10	Nov-10	Dec-10
1										Broccoli	Broccoli	Broccoli	Broccoli
2	Broccoli				Tomato	Tomato	Tomato	Tomato	Tomato	Broccoli	Broccoli	Broccoli	Broccoli
3	Broccoli				Tomato	Tomato	Tomato	Tomato	Tomato	Broccoli	Broccoli	Broccoli	Broccoli
4	Broccoli				Tomato	Tomato	Tomato	Tomato	Tomato	Broccoli	Broccoli	Broccoli	Broccoli

Table All.2 - Allocation factors and total area for each crop.

Field - year	Allocation factor		Field Area	Total area	
	First crop	Second crop		First crop	Second crop
1 – 2008	0.40	0.60	5	2	3
1 – 2009	1		5	5	
1 – 2010	1		5	5	
2 - 2008	$7/12 = 0.58$	$5/12 = 0.42$	5	2.92	2.08
2 - 2009	$8/12 = 0.67$	$4/12 = 0.33$	5	3.33	1.67
2 - 2010	$8/12 = 0.67$	$4/12 = 0.33$	5	3.33	1.67
3 - 2008	$13/16 = 0.81$	$3/16 = 0.19$	5	4.06	0.94
3 - 2009	$9/14 = 0.64$	$5/14 = 0.36$	5	3.21	1.79
3 - 2010	$8/12 = 0.67$	$4/12 = 0.33$	5	3.33	1.67
4 - 2008	$8/12 = 0.67$	$4/12 = 0.33$	5	3.33	1.67
4 - 2009	$7/12 = 0.58$	$5/12 = 0.42$	5	2.92	2.08
4 - 2010	$8/12 = 0.67$	$4/12 = 0.33$	5	3.33	1.67

Appendix III – Calculations to allocate infrastructures for each crop.

Table AIII.1 - Infrastructure information.

Type of Infrastructure	Area/ Volume/ Length	Lifetime considered (years)
Storage Building	600 m ²	50
Pump stations	120 m ³	50
Pipelines	2000 m	20

Table AIII.2 - Calculation of allocated area of the storage building to each field.

Field - year	Allocated area of the storage building to each field (m ²)	
	First crop	Second crop
1 – 2008	$\frac{\left(\frac{2}{20}\right) \times 600}{50} = 1.20$	$\frac{\left(\frac{3}{20}\right) \times 600}{50} = 1.80$
1 – 2009	$\frac{\left(\frac{5}{20}\right) \times 600}{50} = 3.00$	
1 – 2010	$\frac{\left(\frac{5}{20}\right) \times 600}{50} = 3.00$	
2 - 2008	$\frac{\left(\frac{2.92}{20}\right) \times 600}{50} = 1.75$	$\frac{\left(\frac{2.08}{20}\right) \times 600}{50} = 1.25$
2 - 2009	$\frac{\left(\frac{3.33}{20}\right) \times 600}{50} = 2.00$	$\frac{\left(\frac{1.67}{20}\right) \times 600}{50} = 1.00$
2 - 2010	$\frac{\left(\frac{3.33}{20}\right) \times 600}{50} = 2.00$	$\frac{\left(\frac{1.67}{20}\right) \times 600}{50} = 1.00$
3 - 2008	$\frac{\left(\frac{4.06}{20}\right) \times 600}{50} = 2.44$	$\frac{\left(\frac{0.94}{20}\right) \times 600}{50} = 0.56$
3 - 2009	$\frac{\left(\frac{3.21}{20}\right) \times 600}{50} = 1.93$	$\frac{\left(\frac{1.79}{20}\right) \times 600}{50} = 1.07$
3 - 2010	$\frac{\left(\frac{3.33}{20}\right) \times 600}{50} = 2.00$	$\frac{\left(\frac{1.67}{20}\right) \times 600}{50} = 1.00$
4 - 2008	$\frac{\left(\frac{3.33}{20}\right) \times 600}{50} = 2.00$	$\frac{\left(\frac{1.67}{20}\right) \times 600}{50} = 1.00$
4 - 2009	$\frac{\left(\frac{2.92}{20}\right) \times 600}{50} = 1.75$	$\frac{\left(\frac{2.08}{20}\right) \times 600}{50} = 1.25$
4 - 2010	$\frac{\left(\frac{3.33}{20}\right) \times 600}{50} = 2.00$	$\frac{\left(\frac{1.67}{20}\right) \times 600}{50} = 1.00$

Table AIII.3 - Calculation of allocated length of the pipelines for each field.

Field - year	Amount of water (m ³)		Allocated length of the pipelines to each field (m)	
	First Crop	Second Crop	First Crop	Second Crop
1 – 2008	a)	b)	-	-
1 – 2009	4250		$\frac{4250}{67250} \times 2000 = 6.32$	
1 – 2010	3750		$\frac{3750}{67250} \times 2000 = 5.58$	
2 - 2008	b)	3750	-	$\frac{3750}{67250} \times 2000 = 5.58$
2 - 2009	4250	3750	$\frac{4250}{67250} \times 2000 = 6.32$	$\frac{3750}{67250} \times 2000 = 5.58$
2 - 2010	4250	3750	$\frac{4250}{67250} \times 2000 = 6.32$	$\frac{3750}{67250} \times 2000 = 5.58$
3 - 2008	4250	3750	$\frac{4250}{67250} \times 2000 = 6.32$	$\frac{3750}{67250} \times 2000 = 5.58$
3 - 2009	a)	3750	-	$\frac{3750}{67250} \times 2000 = 5.58$
3 - 2010	4250	3750	$\frac{4250}{67250} \times 2000 = 6.32$	$\frac{3750}{67250} \times 2000 = 5.58$
4 - 2008	4250	3750	$\frac{4250}{67250} \times 2000 = 6.32$	$\frac{3750}{67250} \times 2000 = 5.58$
4 - 2009	b)	3750	-	$\frac{3750}{67250} \times 2000 = 5.58$
4 - 2010	4250	3750	$\frac{4250}{67250} \times 2000 = 6.32$	$\frac{3750}{67250} \times 2000 = 5.58$

a) Production of wheat.

b) Production of barley.

Table AIII.4 - Calculation of allocated volume of the pump stations to each field.

Field - year	Amount of water (m ³)		Allocated volume of the pump stations to each field (m ³)	
	First Crop	Second Crop	First Crop	Second Crop
1 – 2008	a)	b)	-	-
1 – 2009	4250		$\frac{4250}{67250} \times 120 = 0.15$	
1 – 2010	3750		$\frac{3750}{67250} \times 120 = 0.13$	
2 - 2008	b)	3750	-	$\frac{3750}{67250} \times 120 = 0.13$
2 - 2009	4250	3750	$\frac{4250}{67250} \times 120 = 0.15$	$\frac{3750}{67250} \times 120 = 0.13$
2 - 2010	4250	3750	$\frac{4250}{67250} \times 120 = 0.15$	$\frac{3750}{67250} \times 120 = 0.13$
3 - 2008	4250	3750	$\frac{4250}{67250} \times 120 = 0.15$	$\frac{3750}{67250} \times 120 = 0.13$
3 - 2009	a)	3750	-	$\frac{3750}{67250} \times 120 = 0.13$
3 - 2010	4250	3750	$\frac{4250}{67250} \times 120 = 0.15$	$\frac{3750}{67250} \times 120 = 0.13$
4 - 2008	4250	3750	$\frac{4250}{67250} \times 120 = 0.15$	$\frac{3750}{67250} \times 120 = 0.13$
4 - 2009	b)	3750	-	$\frac{3750}{67250} \times 120 = 0.13$
4 - 2010	4250	3750	$\frac{4250}{67250} \times 120 = 0.15$	$\frac{3750}{67250} \times 120 = 0.13$

a) Production of wheat.

b) Production of barley.

Appendix IV – Calculations for the inclusion of C sequestration rates in life cycle results

Table AIV.1 – Carbon Sequestration values per crop per year

Type of Crop	Scenario 1			Scenario 2		
	Year 2008	Year 2009	Year 2010	Year 2008	Year 2009	Year 2010
Barley	1.14 x 5.92= 6.73	1.14 x 2.92= 3.32	-	0.55 x 5.92= 3.26	0.55 x 2.92= 1.61	-
Wheat	1.14 x 2.00= 2.27	1.14 x 3.08= 3.50	-	0.55 x 2.00= 1.1	0.55 x 3.08= 1.69	-
Tomato	1.14 x 7.40= 8.41	1.14 x 8.33= 9.47	1.14 x 10.0= 11.37	0.55 x 7.40= 4.07	0.55 x 8.33= 4.58	0.55 x 10.0= 5.50
Broccoli	1.14 x 4.69= 5.33	1.14 x 5.67= 6.44	1.14 x 10.0= 11.37	0.55 x 4.69= 2.58	0.55 x 5.67= 3.12	0.55 x 10.0= 5.50

Table AIV.2 - Weighted mean values of GWP 100-years for the no-tillage scenario, for each crop

Type of Crop	Year 2008	Year 2009	Year 2010	Weighted Mean
Barley	3.29	3.83	-	3,47
Wheat	2.54	3.42	-	3,07
Tomato	5.49	2.93	3.99	4,08
Broccoli	12.80	2.69	5.14	6,22

To calculate the weighted mean values per crop and year were multiplied by the allocated area, summed up and divided by the total area of the crop. In the following a calculation example for barley is provided.

$$\frac{3.29 \times 5.92 + 3.83 \times 2.92}{5.92 + 2.92} = 3.47 \text{ tonCO}_2/\text{ha. a}$$

Table IV.3 - Scenario 1 and 2 for each crop for three years of production

Type of Crop	Weighted Mean	Scenario 1	Scenario 2
Barley	3,47	2.33	4.02
Wheat	3,07	1.93	3.62
Tomato	4,08	2.94	4.63
Broccoli	6,22	5.08	6.77

For example, for barley:

$$Scenario\ 1 = 3.47 - \left(\frac{6.73 + 3.32}{5.92 + 2.92} \right) = 2.33\ tonCO_2eq./ha.a$$

$$Scenario\ 2 = 3.47 + \left(\frac{3.26 + 1.61}{5.92 + 2.92} \right) = 4.02\ tonCO_2eq./ha.a$$