Università degli Studi di Padova

Sede Amministrativa: Università degli Studi di Padova
Dipartimento di Agronomia Animali Alimenti Risorse Naturali e Ambiente - DAFNAE

SCUOLA DI DOTTORATO DI RICERCA IN SCIENZE DELLE PRODUZIONI VEGETALI

CYCLE: XXVI

OPTIONS FOR CLIMATE CHANGE MITIGATION IN AGRICULTURAL SOILS AND IMPACT ON CROP AND GRASSLAND PRODUCTION: A MULTI-SCALE STUDY

Head of the course : Ch.mo Prof. Antonio Berti
Supervisor: Ch.mo Prof. Francesco Morari
Co-Supervisor: Dr. Luca Montanarella (European Commission, DG Joint Research Centre)

PhD student : Francesca Bampa

Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

:::Francesca Bampa, July 31st 2014

A copy of the thesis will be available at *http://paduaresearch.cab.unipd.it/*

Dichiarazione

Con la presente affermo che questa tesi è frutto del mio lavoro e che, per quanto io ne sia a conoscenza, non contiene materiale precedentemente pubblicato o scritto da un'altra persona né materiale che è stato utilizzato per l'ottenimento di qualunque altro titolo o diploma dell'università o altro istituto di apprendimento, a eccezione del caso in cui ciò venga riconosciuto nel testo.

:::Francesca Bampa, 31 luglio 2014

Una copia della tesi sarà disponibile presso *http://paduaresearch.cab.unipd.it/*

Table of contents

Riassunto

La ridotta fertilitá dei suoli è riconosciuta dall'Unione Europea (UE) come preludio di una minore produttivitá delle aree agricole. La Strategia tematica del suolo, prodotta dalla Commissione Europea nel 2006, aveva identificato il declino della sostanza organica come una delle otto principali minacce dei suoli in UE, in quanto il contenuto di carbonio organico è un indicatore della qualitá dei suoli.

Molti studi si sono concentrati su esperimenti a lungo termine a taglio locale. Questo lavoro ha un approccio diverso: a partire da dati ed informazioni a livello UE viene indagato un caso studio a taglio regionale.

L'obiettivo generale di questo lavoro è valutare e quantificare quali sono le pratiche agricole piú promettenti nel preservare o sequestrare carbonio organico nei suoli dell'UE.

La tesi è strutturata in cinque capitoli: il primo è un'introduzione generale sulla necessitá di preservare il carbonio organico presente nei suoli agricoli e una review della legislazione disponibile a livello internazionale ed Europeo. Il secondo capitolo indaga e confronta i dati disponibili sui livelli di carbonio nel suolo a livello UE. Il terzo è una meta-analisi su dati in letteratura sulla capacitá di sequestrare carbonio da parte delle pratiche agricole utilizzate dei suoli dell'UE. Nel quarto capitolo viene applicato il modello CENTURY a livello regionale per ricostruire i valori di stock di carbonio organico attuali e modellare l'applicazione di pratiche agricole promettenti in due diversi scenari climatici. Infine, l'ultimo capitolo riporta le conclusioni generali del lavoro e alcune linee guida.

Parole chiave: agricultura, suolo, modello CENTURY, sequestro di carbonio organico, cambiamenti climatici, Unione Europea, cambiamenti uso e gestione del suolo, pratiche agricole, Regione Veneto, progetto CAPRESE.

Summary

The decline of soil fertility is recognized by the European Union (EU) as the cause of yields reduction in many arable lands. The Soil Thematic Strategy proposed by the European Commission in 2006, identified the decline of organic matter as one of the main soil threats in EU. Organic carbon content is a recognised indicator of soil quality.

Several studies have investigated this relationship through long-term field level experiments. This thesis presents a different approach: starting from data and information at EU level, a regional case study is investigated.

The general objective of this thesis is to evaluate and quantify the impact of specific management practices in preserving or sequestering soil organic carbon in EU and regionally.

The thesis is structured in five chapters: the first is a general introduction on the need for preserving soil organic carbon in the agricultural land and a review on the relevant legislation at international and European level. The second is a scoping chapter that presents a comparison on the available data on organic carbon content at EU level. The third chapter is a meta-analysis on soil organic carbon sequestration data available in scientific literature and reflection the management practices applied at EU scale. In the fourth chapter, the CENTURY model is applied at regional level in order to estimate the actual values of soil organic carbon stock and to model the implementation of the most promising management practices in two different climatic scenarios. The last chapter outlines the general conclusions and recommendations.

Keywords: agriculture, soil organic carbon, CENTURY model, sequestration, climate change, European Union, land-use change, land management practices, Veneto Region, CAPRESE project.

Glossary

BMPs Best Management Practices
CA Conservation Agriculture
CAP Common Agricultural Policy
CBD Convention on Biological Diversity
CEC Cation Exchange Capacity
CT Conventional tillage
EEA European Environment Agency
EC European Commission
ECCP European Climate Change Programme
ESDB European Soil Database
EU European Union
FYM Farmyard manure
GAEC Good Agricultural and Environmental Condition
GEF Global Environmental Facility
GHG greenhouse gas
HWSD Harmonized World Soil Database
IPCC Inter-Governmental Panel on Climate Change
JRC Joint Research Centre
KP Kyoto Protocol
LOI Loss On Ignition
LTE Long Term Experiment
LUCAS Land Use / Cover Statistical Area frame Survey
LULUCF Land Use, Land Use Change and Forestry
MS(s) Member State(s)
NPP Net Primary Production
NT No Tillage
OM organic matter
ppm parts per million
RT Reduced Tillage
SOC soil organic carbon
SOM soil organic matter
SPS Single Payment Scheme
SAPS Single Area Payment Scheme
SCL Soil mapping unit / Climate / Land use
SSSA Soil Science Society of America
UAA Utilised Agricultural Area
UNCBD United Nations Convention on Biological Diversity
UNCCD United Nations Convention to Combat Desertification
UNFCCC United Nations Framework Convention on Climate Change

Chapter

General Introduction

Soil

At the time of the *Plowman's folly, a book* written by Edward H. Faulkner in 1943, a long debate about the management of the soil had already been initiated. Traditionally intensive farming, deep tillage and fertiliser misuse started to be associated with negative impacts on soil such as degradation and loss of productivity(Faulkner, 1943). "*There is nothing wrong with our soils, except our interference*" stated Faulkner in his book and human interference will be the subject of this PhD thesis.

Soil is the uppermost layer of the Earth's crust, a mixture of materials which porosity is due to the aggregation of organic and inorganic particles. It originates from organic residues, geological substrates and anthropogeomorphic[1] products under different physical, chemical and biological conditions (Chesworth, 2008).

Soil **formation** is generally few centimeters in 100 years, depending on: variations in precipitation levels and temperature regimes which determine weathering mechanisms. Critically, climate influences the soil by determining the mass and distribution of plant communities and the rate of decay of organic matter. In parallel, climate also drives pedogenic processes such as leaching, the mobilisation of clay minerals and nutrient exchange mechanisms, which give soils their characteristic properties. Generally soil erodes 12 times faster on average that it forms (Chesworth, 2008). Soil formation rates have been estimated for current European Union (EU) conditions at about 0.3 to 1.2 Mg ha^{-1} yr^{-1} (i.e. 30 - 120 g m^2 yr^{-1}) (Verheijen *et al.*, 2009). Erosion rates range between 10 to 20 Mg ha^{-1} yr^{-1} have been estimated for some European arable soils although highly dependent on time and space. Verheijen *et al.*, (2009) proposed the concept of *tolerable soil erosion*: the soil formation rates proposed should be used for Europe as tolerable soil erosion rates.

Soil is a non-renewable resource and performs many biospheric **functions**[2]: (a) provides food, biomass, raw materials and habitat for organisms; (b) acts as reservoir, stores, redistributes, regulate, filters and transforms substances, including water, solar energy, nutrients and carbon (C); (c) gene and biodiversity pool; (d) platform for human and socio-economic activities; (e) storage of geological and archaeological heritage; (f)

[1] unconsolidated mineral or organic materials produced by human activity
[2] the following list of soil functions is a merging of different sources

sustain biological activity, diversity, and productivity; (g) filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal by-products and atmospheric deposition (Karlen *et al.*, 1997; Chesworth, 2008; EC, 2012a; Schulte *et al.*, 2013).

Soil, seen as a system, is a vulnerable part of the biosphere. It is subject of continuous dynamic changes and prone to **degradation** due to environmental (e.g. water, temperature, etc.) and human drivers (Chesworth, 2008). Soil degradation refers to the incapacity of soils to produce economic goods and to perform the above mentioned ecologic functions (Bridges & Oldeman, 1999; Seybold *et al.*, 1999). Changes in climatic conditions (e.g. extreme weather events such as rising temperatures, changing precipitation intensity and frequency) are thus likely to affect soil-related bio-geophysical processes and environmental services that are regulated by soil. Negative processes such as erosion, decline in organic matter, contamination, landslides and many more bring to loss of fertile soil and exacerbate greenhouse gas emissions (GHG) from soil. All this threats are often driven by human activity such as inadequate agricultural and forestry practices, industrial activities, tourism, urban and industrial sprawl and construction works (EC, 2006a, 2012a). These activities have a negative impact, preventing the soil from performing its broad range of functions and services to humans and ecosystems. Soil degradation has in turn a direct impact on water and air quality, biodiversity and climate change.

The contribution of soil to productivity is called **soil fertility** and it depends on its texture, aeration, temperature, biology and microbiology, availability of nutrients, pH, organic matter, salinity and alkalinity. The *Soil Science Society of America* defines soil fertility as ‘‘the quality of a soil that enables it to provide nutrients in adequate amounts and in proper balance for the growth of specified plants or crops’’[3]. Accordin to the Natural Resources Conservation Service, **soil quality** is “the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation”(Creamer *et al.*, 2010, Allan 1995, EUR23438 EN,2008). For the human community, soil quality services could be regarded as the ability of soil to: protect the

[3] https://www.soils.org/publications/soils-glossary

environment, produce food, perform waste disposal, provide foundation for infrastructures, biodiversity and human health (Chesworth, 2008). The soil capacity to provide a specific function cannot be measured directly but it can be indirectly inferred through indicators of the above mentioned functions (Karlen *et al.*, 1997; Seybold *et al.*, 1999). Maintaining and improving soil quality is crucial for a sustainable agricultural productivity (Jandl *et al.*, 2014). One of the critical soil quality indicators is the organic carbon (OC) content (Reeves D. W., 1997; Lal, 2004a, 2004b; Jandl *et al.*, 2014), because of its impact on other indicators and its role as a proxy for soil quality (Paul Obade & Lal, 2013). The role of OC in soil, mainly agricultural soils, will be discussed in the following paragraphs.

Soil protection policy

The concept of soil as a vital non-renewable resource to protect has been acknowledged worldwide and the role of society towards its protection is gaining more and more policy attention (Blum, 2005; Creamer *et al.*, 2010a; Goebel *et al.*, 2011; Ashton, 2012; Schulte *et al.*, 2013).

Starting from the panorama, the three major *Multilateral Environmental Agreements* (MEA) negotiated in 1992 at the Rio Conference (UNFCCC, 1992), addresses respectively the three conventions on climate change (UNFCCC[4]), biological diversity (UNCBD[5]) and desertification (UNCCD[6]). These conventions are closely linked to soil and its evolution over time, because of its mitigation potential, its great pool of biodiversity (Midgley *et al.*, 2010) and because it represents an indicator of desertification (Schwilch *et al.*, 2012). Despite their global authority, with their lengthy negotiation processes, binding MEASs have shown their limits during the past 20 years. The Conventions lack the scientific foundation necessary to drive soil protection (Kibblewhite *et al.*, 2012).

In the article 3.4 of the *Kyoto Protocol*, the United Nations Framework Convention on Climate Change (UNFCCC) recognizes the capacity of soils - agricultural, land use change and forestry category- to store C and the mitigation potential, both in terms of

[4] http://unfccc.int/
[5] www.cbd.int
[6] http://www.unccd.int/

enhancement of the C sink and reduction in CO_2 emissions. Article 3.3 declares the need to establish the levels of C stocks in 1990 and to estimates the changes in subsequent years (Smith *et al.*, 1997a; UN, 1997).

In the UN conference on Sustainable Development, known as “Rio+20” in 2012, the world leaders gathered to agree on a sustainable goal for land. The proposed *Sustainable Development Goal of a “Zero Net Land and Soil Degradation World*” paves the way towards a renewed global effort on land, soil protection and restoration activities, to support food security and poverty eradication. The goal needs to be achieved by 2030 and will require the commitment of both public and private sectors (Ashton, 2012). In this conference a new approach to sustainability and environmental issues has been put forward, based on partnerships and “coalitions of the willing”.

An initiative by the Food and Agriculture Organization of the United Nations (FAO), with the strong support of the European Commission, has been put forward since 2011, proposing a Global Soil Partnership (GSP) as an interactive, responsive and voluntary partnership, open to governments, regional organizations, institutions, decision makers and other stakeholders[7]. This voluntary community is in favour of more effective measures to protect natural resources for future generations and is willing to form a voluntary partnership to move forward with more ambitious agendas. The GSP aims to address a sustainable management of global soil resources and federate all the stakeholders and parties voluntarily willing to move on with effective soil protection measures. This science-policy interface tries to address all the policy relevant scientific and technical issues related to soils (Montanarella & Vargas, 2012, SCOPE chapter). Full implementation of the GSP started in 2013 with the establishment of an Intergovernmental Technical Panel on Soils (ITPS) which members should provide scientific and technical advice on global soil issues. Within the framework of the GSP, the 68th UN General Assembly, past December 2013, declared the **December 5th** as the **World Soil Day** and **2015** the **International Year of Soils**, a global awareness raising platform that aims to celebrate the importance of soil as a critical component of the natural system and as a vital contributor to human wellbeing (A/C.2/68/L.21).

---

[7] http://www.fao.org/globalsoilpartnership/mandate-rules-of-procedure/en/

At European Union level, the European Commission elaborated in 2006 the *Thematic Strategy for Soil Protection* (COM (2006)231 final, COM (2006) 232 final), reiterated in *The implementation of the Soil Thematic Strategy and on-going activities* (COM (2012)46 final). The overall objective of the Strategy was to establish a Soil Framework Directive for the protection and the sustainable use of soil, by preventing further soil degradation, preserving biophysical functions, and by restoring degraded soils taking into account the different land uses. Moreover the Strategy highlights how soil is subject to a series of threats such as: erosion, decline in organic matter, local and diffuse contamination, soil sealing, compaction, decline in biodiversity, salinisation, floods and landslides (EC, 2006a, 2006b, 2012a). However in October 2013 the European Commission, in order to evolve its policy programme, elaborated *REFIT*[8] - *the Regulatory Fitness and Performance Programme: Results and Next Steps* (COM(2013) 685 and its Annex). The EU legislation reviews proposed the withdrawal of the pending proposal for a Soil Framework Directive, stalling since 2006. A possible way forward on soil protection at EU level was discussed on 3rd of March 2014. The debate indicated that protecting soils remained an important objective for the EU, despite the fact that, in its present format, the proposal could not be agreed by UK, France, Germany, Austria and the Netherlands. In light of the above, the Commission on 30th April 2014 took the decision to withdraw the proposal for a Soil Framework Directive (OJ C 153 of 21 May 2014 and corrigendum in OJ C 163 of 28 May 2014).

The 7th Environment Action Programme, guiding EU environment policy until 2020, recognises soil degradation as a serious challenge and to address soil quality issues using a targeted and proportionate risk-based approach within a binding legal framework. to be reflected by EU as soon as possible (EU, 2013a). For example some papers proposed a concept of "functional soil planning", based on maximizing the seven EU soil functions at national and international level by customizing soil management (i.e. land use and soil type) at local level (Smith *et al.*, 2007a; Creamer *et al.*, 2010a; Bouma *et al.*, 2012; Schulte *et al.*, 2013) .

[8] http://europa.eu/rapid/press-release_IP-13-891_en.htm and http://europa.eu/rapid/press-release_MEMO-13-833_en.htm

The framework for actions of the *Resource Efficiency Roadmap of the Europe 2020 Strategy* includes many policy areas such as climate change, energy, transport, industry, raw materials, agriculture, fisheries, biodiversity and regional development (EC, 2011).

The Roadmap aims to set out a framework for the design and implementation of future actions oriented to resource efficiency. Soil and land related milestones indicates that EU policies by 2020 must take into account their direct and indirect impact on land use in the EU and globally. The rate of land take should be on track with the aim to achieve zero net land take by 2050, soil erosion should be reduced and organic matter increased, with remedial work on contaminated sites well underway (EC, 2011). In order to respond to the Roadmap and to the Rio+20 UN conference[9] political mandates, the Commission is working on a Communication[10] on "*Land as a resource*", expected for 2015 to ensure a sustainable EU land management.

Lacking a "soil directive", there are other EU policies that address soil and its protection as secondary objective or indirectly: the Nitrates Directive (COM 91 ⁄ 676 ⁄ EEC); the Habitats Directive; the Sewage sludge directive; the Water Framework Directive (COM 2000 ⁄ 60 ⁄ EC, 2000); Natura 2000; the Common Agricultural Policy (CAP) with the Good Agricultural and Environmental Conditions (GAEC) (EC, 1257/99, EC, 1259/99); regulations regarding organic pollutants and heavy metals, dioxins and dioxin-like PCBs (COM 2002 ⁄ 69 ⁄ EC, 2002); impure fertilizer (EC 2003 ⁄ 2003,2003) and veterinary medicinal products (COM 2001 ⁄ 82 ⁄ EC, 2001).

The Nitrates Directive through the nutrient budget plans addresses the organic fertilizers inputs. The Nitrate Directive together with the Water Framework Directive, the Resource Efficiency roadmap, the Floods Directive and the Adaptation Strategy legislates the use of cover crops, the incorporation of residues and the no tillage practice. The Birds & Habitat Directives, together with the above mentioned policies, targets grasslands protection and re-conversion, cropping system in perennial grassland, peatland protection and restoration. However the underpinning policy mechanisms behind are always linked to the Common Agricultural Policy (CAP).

---

[9] http://www.uncsd2012.org/thefuturewewant.html

[10] http://ec.europa.eu/environment/land_use/index_en.htm

The EC's communication on *The CAP towards 2020* proposed options for the CAP after 2013 on how farming practices could limit soil depletion, water shortages, pollution, C sequestration and loss of biodiversity (EC, 2012b). The reform of the CAP agreed on 26th of June 2013, saw four Basic Regulations formally adopted and published on 20th December 2013. The CAP reform 2014-2020 contains a new greening architecture and a land-based approach that recognises soil as one of the environmental factors driving agriculture. The reform calls on the agricultural community to improve its environmental performance through more sustainable production methods. Farmers should adapt to changes to the climate by pursuing relevant mitigation and adaptation actions (e.g. resilience).

The CAP schemes for the agricultural areas eligible for direct payments are:

Cross-compliance – Regulatory

Through its Statutory Management Requirements and the Good Agricultural and Environmental Condition (GAEC) these obligations can play an important role in the protection, conservation and improvement of soil and C stock. Through the GAEC systems, farmers have to: limit soil erosion with land management practices that reflect site specific conditions; maintain SOM level through appropriate practices including: a) a ban on burning arable stubble; b) ensure a minimum level of soil cover; c) protect and manage water, including safeguarding of water bodies and groundwater against pollution caused by nitrates from agricultural sources; d) establish buffer strips; e) conserve landscape features (e.g. hedges, ponds, ditches, trees in line, in group or isolated, field margins and terraces) (EU, 2009, 2013b). The regulation n° 1306 establishes that the Farm Advisory System should address the impact of climate change mitigation and adaptation in the relevant region, the impact of the farming practices respect to GHG emissions and the contribution of the improved farming and agroforestry practices to mitigation. The system should also help farmers with information on how to improve and optimise soil C levels (EU, 2013b).

Green direct payment – Mandatory

In this Pillar 1 of the CAP, all Member States have to develop proven measures to help farmers maintain and improve soil and water quality, biodiversity and meeting the challenges of climate change. Specifically 30% of the national direct payments rewards farmers for respecting three environmentally-friendly agricultural practices on Utilised Agricultural Area (UAA): (1) crop diversification, (2) maintenance of permanent grasslands; (3) conserving 5%, and later 7%, of ecological focus areas of interest as from 2018 or measures considered to have at least equivalent environmental benefits (EC, 2013).

Rural development - Voluntary

In this Pillar 2 of the CAP, at least 30% of the Rural Development programme’s budget must be allocated to voluntary measures, including agri-environmental measures (e.g. reductions in fertiliser and plant protection products, extensification of livestock conversion of arable land to grassland and rotation measures; under-sowing, cover crops and strip crops, etc..), organic farming, Areas of Natural Constraints, Natura2000 sites, forestry measures and soil-friendly investments (e.g. harvesting machinery) or innovation measures. The Regulation is clear as to how the payments should support the sustainable development of rural areas and encourage agricultural practices that contribute to climate change mitigation and adaptation that are compatible with the protection and improvement of the soil and its management (e.g. biodiversity and high nature value farming systems). Mitigation action should aim to limit emissions in agriculture from activities such as livestock production and fertilizer use. C sinks should be preserved and C sequestration enhanced. These measures, locally adapted, could significantly enhance soils and OM levels and related ecosystem services. EU Regulation n° 1305 aims to promote resource efficiency and supports the shift towards a low C and climate resilient economy in agriculture with a focus on: efficiency in water use; reducing GHGs and N emissions from agriculture; fostering C conservation and sequestration (EU, 2013c).

Organic carbon in agricultural soils

The interference examined in this thesis concerns the decline of organic matter in the agricultural soils of the EU (EC, 2006a, 2006b, 2012a).

As mentioned previously, the organic carbon content of the soil (SOC) is a major indicator for soil functions and ecosystem services (Smith, 2004a), water holding capacity and susceptibility of the land to degrade.

Both SOC and SOM are terms used in scientific literature, by convention:

$$SOM = 1.724^* \times SOC$$

where the conversion factor* can range from 1.4 to 3.3 (Korschens *et al.*, 1998)

While data and information in this thesis refer to SOC, for qualitative information the term SOM is preferred to simplify the reading.

Referring to the global C cycle the biological fixation of CO_2 or photosynthesis to produce organic compounds is defined as gross primary production (GPP). After losses to respiration, growth and maintenance the newly formed biomass is defined as net primary production (NPP). The decomposition of NPP leads to the selective preservation of some resistant plant constituents, such as lignin. In addition, the turnover of microorganisms (i.e. humus formation) produces compounds precursors to stable soil C. The Soil Science Society of America (SSSA) defines SOM as the total organic fraction of the soil exclusive of undecayed plant and animal residues. The surface litter and living animals are generally not included as part of SOM. In the Soil Thematic Strategy SOM is defined as “the organic fraction of the soil, excluding undecayed plant and animal residues, their partial decomposition products, and the soil biomass” (EC 2006). The structure of SOM consists of approximately 50–55% C, 5% hydrogen, 33% oxygen, 4.5% nitrogen, and 1% sulphur and phosphorous plus trace elements and micronutrients, such as Ca, Zn and Cu (Chesworth, 2008). Plants can be grown without SOM equally well in hydroponic systems, but research has showed the important role of SOM as reservoir of essential plant nutrients and its effect on the physical (i.e. aeration, water infiltration and storage), chemical (i.e. nutrient cycling), and biological properties of soil. It is not only the quantity, but also the quality that is relevant for the effect of SOM, beneficial for crop production and soil conservation. Trends in SOM levels are driven by both natural and human factors activities. Anthropogenic factors include the conversion of grassland, forests and natural vegetation to arable land; deep ploughing of arable soils; drainage, liming, N fertiliser use; tillage of peat soils and unsustainable crop rotations without temporary grasslands (Van-camp *et al.*, 2004; Zdruli *et al.*, 2004). The human factors will be discussed in more details in the chapter III. Example of natural factors, include higher temperatures that favour the decomposition of OM, which releases nutrients, especially nitrogen, in a plant-available form. Therefore, the OM content in soils of warmer climates is often lower. Increased soil moisture or natural succession of vegetation communities can also affect SOM levels.

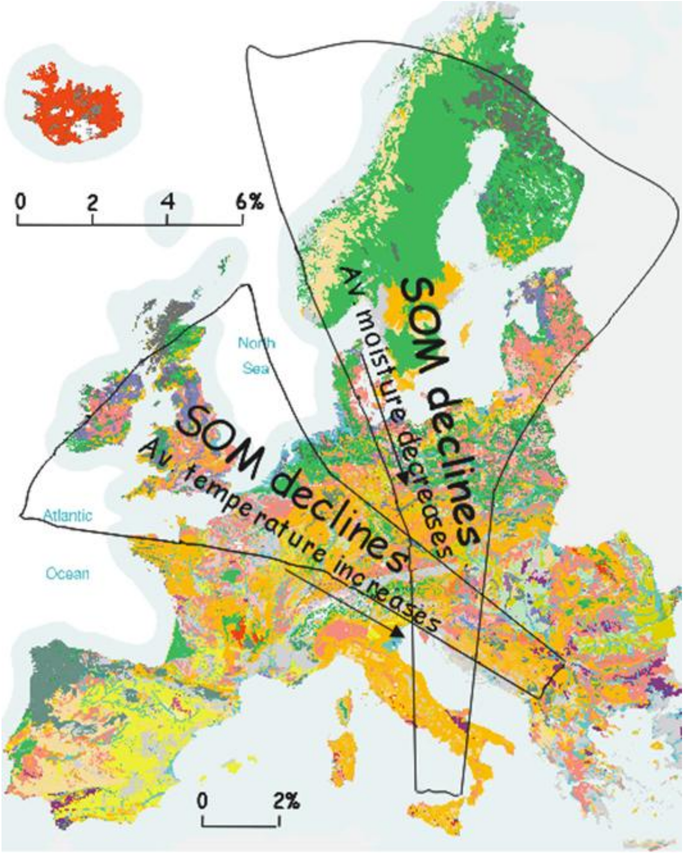


Figure 1.1 – Influence of temperature and moisture on SOM content in Europe (Zdruli Jones, R.J.A. and Montanarella, L, 2004; Bellamy *et al.*, 2005a)

Returning to the concept of soil productivity, SOM content often increased it and represents one of the soils factors that determine the capacity to produce crops (Chesworth, 2008). All the factors that have a negative impact on SOM, are reflected in a deterioration of the soil or prevention of the soil from performing its broad range of functions and ecosystems services. King et al (1995) gives the value of 2% as guide value in soils for SOM levels. This critical limit of 2%, below which lack of cohesion and instability characterize the soil it has been postulated investigating structural deterioration of SOM levels in arable soils (Lal & Greenland, 1979). This limit has subsequently been shown to be a 'guide-value' rather than a critical one, but the principle holds true and the perceived decline has continued (Loveland & Webb, 2003)

In relation to the terrestrial ecosystems storage, atmospheric CO_2 in the form of plant materials, plant residues and other organic solids is sequestered or retained is soils as part of the organic carbon (OC) stock (Olson, 2010, 2013). The SOC pool is the largest terrestrial reservoir of carbon, containing twice the amount of carbon in the biosphere and atmosphere combined (Batjes, 1996, 2004; Bellamy *et al.*, 2005b; Stockmann *et al.*, 2013). The global SOC pool in the top three meters of soil has been estimated at 2344 Pg C, of which 1502 Pg are contained in the uppermost meter (Batjes *et al.*, 1996; Jobbágy & Jackson, 2000; Guo & Gifford, 2002; Stockmann *et al.*, 2013). Very recent estimates (Batjes, 1996) have revised the global soil C pool to 684-724 Pg of C in the upper 30cm, 1462-1548 Pg of C in the upper 100cm and 2376-2456 Pg of C in the upper 200cm. This SOC stock reflects the history in land use and management, soil type, hydrology and climatic conditions: over long periods the C stock varies mainly due to climatic, geological and soil forming factors, but for short periods vegetation disturbances and land use changes affect the storage (Batjes, 1996).

EU-27[11] topsoils (the upper part of the solum, essentially the part affected directly by ploughing, also referred to as the A horizon) represents 5% of the total global SOC pool. The EU-27 topsoils pool of OC accounts currently to a stock of around 75.3 Pg of C (according to USDA and 79.7 according to EU – DG JRC data), of which 20% is represented by peatlands and 50% is located in Sweden, Finland and UK (areas that are rich in peat soils) (Schils, 2008).

Changes in SOC levels are difficult to measure, since C stocks changes slowly (Kätterer *et al.*, 2004) However, it is important to investigate fluxes as changes in SOC stocks may influence atmospheric CO_2 concentration (Soderstrom *et al.*, 2014). Changes in land use have oxidized superficial soil C stocks exacerbating GHG emissions, mainly CO_2 (IPCC, 2007). SOC stocks can be seen as a potential **source** of greenhouse gases (GHGs) through the formation of CO_2, CH_4 and N_2O but they can be also regarded as a **sink** through the process of **C sequestration** through biological process (Van-Camp *et al.*, 2004, Batjes, 2014).

Soil carbon sequestration process has a range of definitions available:

[11] EU-27 stands for 27 Member States of the EU, only recently Croatia became the 28th

- "net removal and storage of atmospheric CO2 securely in the soil (Lal, 2004b, 2004c)."
- "net transfer of C from the atmosphere to the soil at the global scale, where a local net accumulation of C (e.g. manure application) does not necessarily lead to C sequestration. Limitation are: finite quantity of C stored in soil; reversible process and dependent on climate and other GHGs (Powlson *et al.*, 2011; EC, 2014)."
- "transfer of CO2 from the atmosphere into the soil through plants, plant residues and other organic solids, which are stored or retained as part of the SOM (humus). The retention time of sequestered C in the soil (terrestrial pool) can range from the short-term (not immediately released back to atmosphere) to long-term (millennia) storage. The sequestrated SOC process should increase the net SOC storage during and at the end of a study to above the previous pre-treatment baseline levels and result in a net reduction in the CO2 levels in atmosphere". The phrase "of a land unit" needs to be added to the definition proposed by Olson (2010) to add clarity and to prevent the loading or adding SOC to the land unit soil naturally or artificially from external sources. Carbon not directly taken from the atmosphere and from outside the land unit should not be counted as sequestered SOC. These external inputs could include organic fertilizers, manure, plant residues, or topsoil or natural (Olson, 2010, 2013).

The main factors determining the amount of C sequestered in soil are:

- the rate of input of OM;
- the decomposability of the OM inputs, in particular the light fraction OC;
- the depth in the soil at which OC is placed;
- the physical protection of intra-aggregate or organo-mineral complexes.

The retention time of sequestered C in the soil (terrestrial pool) can range from the short-term (i.e. not immediately released back to atmosphere, in term of years) to long-term (millennia).

In the recent years the concept of combating climate change by sequestering C in the soils has engaged many scientists. What is agreed is that the effect of the predicted climate warming will speed up the decay of organic matter at an overall rate of 11–34 Pg of C per degree Celsius of warming (Parton *et al.*, 1994; Batjes, 1996), thereby releasing CO_2

to the atmosphere which will further enhance the warming trend. It is expected that the major decline of organic matter should occur in areas currently under cool and wet climatic conditions. Consequently, in Italy, soil degradation might progressively affect upland soils from south to north (E. A. C. Costantini, 2013).

So far the information on the impacts of climate change on EU soils is very limited: changes are likely due to projected rising temperatures, changing precipitation patterns and frequency, and more severe droughts. Such changes can lead to a decline in SOC content and an increase in CO_2 emissions. Variations in rainfall patterns and intensity are increasing soil erosion affecting soil moisture mainly in the Mediterranean region and in north-eastern Europe. Furthermore, prolonged drought periods due to climatic changes may contribute to soil degradation and increase the risk of desertification in the Mediterranean and Eastern Europe. On the other side there are also positive changes linked to higher CO_2 levels emission ̀s in the atmosphere. (EEA, 2010).

Clearly agriculture has a major effect on the ecosystem as it shapes the landscape (i.e. land cover and land use), culture and history. Farming uses water and occupies land, but it can also protect them, secures food to the local population and preserves traditions and management practices that might otherwise be lost. Following (Betts *et al.*, 2007) agricultural soils occupy about 35% of the global land surface and approximately 12% of the soil C stock is present in cultivated soil (Schlesinger, 1997). The LUCAS (Land Use / Cover Statistical Area frame Survey) of EUROSTAT, reported that in 2010 almost 40% of the EU was covered in 2010 by forests and other wooded areas (Palmieri *et al.*, 2011). Croplands occupied 24% and grasslands 20%. The highest shares of land cover by crops was found in Denmark (48%), Hungary (47%), Poland (36%), Czech Republic (35%), Germany and Italy (both 33%), Spain and France (both 30%). Almost two thirds of Ireland (64%) is covered by natural or agricultural grasslands (i.e. permanent pastures, rough grazing, meadows) grasslands, followed by the United Kingdom (42%), the Netherlands (38%) and Belgium (33%). Analysis of the CORINE Land Cover (CLC) database for 2006 gives slightly different values that reflect not only a different base line, but also a different mapping approach and different class definitions. In comparison, CORINE 2006 reported that almost 35% of the EU is covered by forests and other wooded areas while the extent of arable areas pasture and permanent crops came to 33%, 12% and 3%, respectively.

The provision of detailed data on SOC stocks in the agri soils of the EU is a priority and it's necessary to develop appropriate management practices (EC, 2012a), because not single EU policy overarch SOC and land management. For this reason is necessary to refer to a number of other policy areas to target soil and C management indirectly or as a secondary object. Future EU policies on agriculture will address land condition and will utilize SOC as indicator of soil quality and as a strategy to offset CO_2 emission through C sequestration. According to EU figures agriculture was responsible for 9.6% of the EU-27 total and 6.6% of Italy's GHGs emissions (CO_2 equivalent), a trend that has been constant in recent years (EEA, 2010; Jones *et al.*, 2011). Approximately 50% of EU agricultural GHGs emissions derive from soil in 2010 (EEA, 2010). However a consistent picture of EU agricultural SOC stock to orient the future policymaker decisions is lacking . In the contest of CAPRESE project this issue has been investigated and will be discussed in Chapter III and IV.

Having a substantial proportion of the EU soils devoted to agriculture (i.e. cropland and grassland), it is clear that this sector can play a significant role in managing GHG fluxes, by maintaining or even increasing SOM levels (EC, 2009a). Agriculture is very sensitive to climatic variations and has to constantly adapt its practices to ensure a sufficient and high quality food production. There are two main priorities in relationship to climate change: (1) **climate change mitigation** by reducing its GHGs direct and indirect emissions (e.g. through the use of fertilizers); by storing C into soils (intending soils as a CO_2 sink) and by producing renewable raw materials that substitute energy intensive fossil fuels (EC, 2009b); (2) **adaptation** to the new climatic conditions (e.g. increased temperatures, droughts, increased climatic variations, etc.) in order to ensure a sufficient maintenance of productivity while maintaining agriculture as an important contribution to rural development. Agricultural activities are recognised both as source of GHG emissions but also as potential contributors to climate change mitigation by reducing its emissions, by the production of renewable energies and bio products, and by storing C in farmland soils (EC, 2009c) The level of contribution depends *inter alia* on factors such as soil types, climatic conditions and land use (Jandl & Olsson, 2011).

Managing agricultural land in an efficient way can positively affect the soil functions while maintaining the same rate of food production. Better soils raise farm yields and incomes, improve food security, deliver secondary ecosystem benefits and should make agriculture more resilient to climate change (Lal, 2006, 2010a, 2010b, 2010c). In order to achieve this goal, attention should be focused on practices that could maintain and enhance the level of C in soils (Lal, 2006, 2011a). In the past decade (2000-2010) a large number of publications on soil C sequestration have indicated the possibility to sequester C through the implementation of specific land management practices in agriculture (Freibauer *et al.*, 2004; Smith *et al.*, 2008a).

A major issue is to improve the knowledge-base on EU SOC data, especially on harmonised geo-referenced measurements nd from national surveys of Member States (MS). A second goal would be to better understand the OC dynamics over time together with the impacts of management practices on SOC stocks. This acquired knowledge could permit the establishment of targeted areas where action is most urgently required and to recognize which land use and land management practices could be implemented to deliver the optimum climate change mitigation response. The following chapters of the thesis will focus on these knowledge gaps.

An introductory note on the case study area

The Veneto Region of northern Italy has a total area of 18 398,9 km^2 with a population of about five million people. The Veneto Region has a temperate sub-continental climate with an annual mean temperature range of 10-14.4°C. Annual precipitation ranges between 600 to 2000 mm (1061 mm in 2012 while for the period 1992-2011, 1.075 mm following ARPAV (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto) statistics[12]); this gives good climatic and hydrogeological conditions for forestry and agriculture development Annual isohyets have a N-E to S-W direction with 1600 mm in the Alps (max 2000-2200 mm), 1100-1600 mm in the pre-Alps and 600-1100 mm in the Veneto plain (ARPAV source website).

The region is divided into six administrative provinces: Verona Vicenza, Padova, Rovigo, Venezia and Belluno.

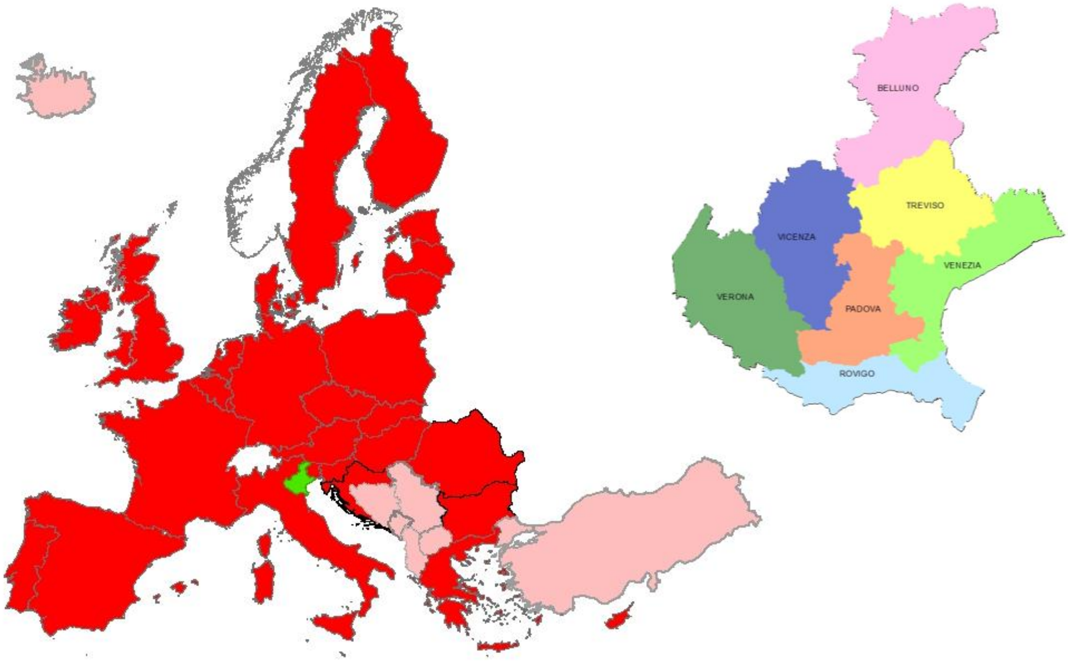


Figure 1.2 – EU Member States (MSs) in red, EU candidate countries in pink, Veneto Region in green and the provinces of Veneto Region on the right.

[12] http://www.arpa.veneto.it/arpavinforma/indicatori-ambientali/indicatori_ambientali/clima-e-rischi-naturali/clima/precipitazione-annua/view

The morphology of Veneto Region is complex due to the presence of different physical features: more than 56% of the region is made up of plains, 29% mountains and almost 15% hills. More than three quarters of the Veneto's 4.9 million plus inhabitants live on the plains, whereas, of the remaining quarter, 16.5% live in the hills and 7.1% in the mountains (Veneto, 2011). The Alpine zone is typical of the Prealps and alpine valleys of Vicenza and Belluno province. This area is richly forested. The hill zone lies north of Treviso, covering Colli Euganei of Padova and Colli Berici in Vicenza province. This area is rich in vineyards, on average inhabitated and contains limited forested areas. Often forestry divides the different agricultural areas. The coastal zone includes large coastal lagoons, more than 150 km of beaches and the eastern bank of Lago di Garda, the largest lake in Italy.

The study area covers the entire Venetian plain, part of the Po valley, and includes the vulnerable zones area as declared by Nitrate Directives: vulnerable zones (see Chapter IV). The plain is divided into two distinct areas, the *Alta Pianura* (Upper Plain) and *Bassa Pianura* (Lower Plain), which are separated by a line of springs. The *Alta Pianura* is mainly made up of highly-permeable gravelly materials in the form of large pebbly conoids, created over time by the continual meandering of the rivers draining the adjacent mountains; the *Bassa Pianura* is made up of finer sediments-sand and clay-that decrease in size from the mountains towards the valley (Veneto, 2011). The lower plain covers entirely the provinces of Rovigo, Venezia and Padova and partly Vicenza and Treviso. This area has a temperate climate, with mean annual temperatures never fall below 13°C and annual precipitations between 700 and 1100 mm. Densly populated after the Second World War, the region is occupied by urban areas and intensively cultivated agricultural land.

The Veneto Region has extensive water elements, both groundwater and surface, whose hydrographic network is made up of: (a) six catchment areas of national importance (i.e. Adige, Brenta-Bacchiglione, Livenza, Piave, Po and Tagliamento); (b) two of interregional importance (i.e. Fissero-Tartaro-Canalbianco and Lemene); (c) three of regional importance (i.e. the drainage basin of the Laguna di Venezia, the plain between Livenza and Piave, and Sile) (Veneto, 2011).

The UAA (known in Italian known as the *Superficie Agricola Utilizzata* - SAU[13]) denotes land that is suitable for agricultural production including arable crops (i.e. annual crops, technical crops and fallow), permanent crops (i.e. orchards and vineyards) and permanent pastures (i.e. natural grasses and livestock grazing). SAU includes the real surface used in agriculture and not the potential.

Agriculture in the Veneto is an critical feature for its economy, culture, food production, territory and environment: approximately 811,440[14] hectares of UAA are suitable for production. This shows how the territory is strongly shaped and influenced by its farming activities. Following the 2013 Statistical Report many agricultural areas are at risk due to the risk of landslides because much of the land has been degraded or abandoned. In the past ten years (2000-2010) the number of small agricultural holdings fell in favour of larger and more specialised operations while the number of food-related businesses increased. In the past 30 years (1980s – 2010) half of the Region's small holdings (< 1ha, mainly winemakers) disappeared (equal to 11% of SAU - more than 100,000 ha). The crop production and livestock sector did not change significantly: more than two thirds of the UAA are committed to arable land, with a decrease of grasslands and pastures (see Chapter IV).

Table 1 – Historical series of UAA (ha) for provinces and for Veneto region (Istat 2010[15]).

Province	1970	1982	1990	2000	2010
Verona	198154,4	186728,7	180962,7	177520,3	173161,8
Vicenza	143723,3	127659,9	119486,9	114170,3	94528,6
Belluno	73247,1	69018,1	55188,4	52893,3	46942,1
Treviso	163956,9	148073,4	142641,3	138493,7	128581,0
Venezia	134057,0	123891,9	122940,9	119995,3	111812,9
Padova	157728,4	141905,6	140506,0	135668,1	138498,6
Rovigo	120397,4	116739,9	119541,4	114002,8	117915,0
Veneto (tot)	991264,4	914017,4	881267,5	852743,9	811440,0

[13] http://www.consiglioveneto.it/crvportal/upload_crv/serviziostudi/1372687215191_Veneto_Tendenze3_2012.pdf
[14] http://noi-italia.istat.it/
[15] http://statistica.regione.veneto.it/jsp/cenagr2010.jsp?ntab=1

Objectives

The general objective of this PhD project is to individuate the most relevant land management options for EU agricultural soils and their impact (preservation and sequestration) on soil organic carbon stocks.

Three sub-objectives are: (a) a comparison and validation of the available soil organic carbon data at EU level (EIONET and LUCAS databases); (c) an assessment of soil organic carbon sequestration rates through a meta-analysis of scientific literature; (c) the development of a agro-ecosystem SOC simulation model with existing SOC database.

The methodology in order to deliver the objectives used: LUCAS - Land Use/Cover statistical Area Frame Survey- general soil survey 2009 (data on SOC belonging to year 2009 considered t0) and a regional LUCAS soil survey database dated 2011, plus data on the '90ies coming from the regional case study (Veneto – ARPAV). The application of model CENTURY has been used for calibration and prediction of t1.

This work is part of a research study funded by **European Commission – DG Joint Research Centre (JRC)** in partnership with **Universitá degli studi di Padova – DAFNAE – PhD School of Crop Sciences.** The research has been carried out to support the European Commission – DG Agriculture and Rural Development under the Administrative Arrangement N° AGRI-2012-0166 between DG AGRI and DG JRC on the study: "**CA**rbon **PRE**servation and **SE**questration in agricultural soils - options and implications for agricultural production (**CAPRESE soils**)[16]". The study aimed to determine the geographical distribution of the potential GHG mitigation options, focusing on hot spots in the EU, where mitigation actions would be particularly efficient.

[16] http://eusoils.jrc.ec.europa.eu/library/Themes/SOC/CAPRESE/, http://mars.jrc.ec.europa.eu/mars/Projects/CAPRESE

References

Ashton, R. (2012). *Zero Net Land Degradation. A Sustainable Development Goal for Rio+20* (p. 32). Bonn, Germany : UNCCD.

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, *47*(1), 151–163. doi:10.1111/ejss.12114_2

Batjes, N. H. (2004). Soil carbon stocks and projected changes according to land use and management: A case study for Kenya. *Soil Use and Management*, *20*, 350–356. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-7944223507&partnerID=40&md5=204cd238be35e61fe72e900159559ee4

Bellamy, P. H., Loveland, P. J., Bradley, R. I., Lark, R. M., & Kirk, G. J. D. (2005). Carbon losses from all soils across England and Wales 1978-2003. *Nature*, *437*(7056), 245–248. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-24644485331&partnerID=40&md5=5bdc0b9138793ac6602a55475391dbc4

Bellamy, P. H., Loveland, P. J., Bradley, R. I., Lark, R. M., & Kirk, G. J. D. (2005). Carbon losses from all soils across England and Wales 1978-2003. *Nature*, *437*(7056), 245–248. doi:10.1038/nature04038

Betts, R. A., Falloon, P. D., Goldewijk, K. K., & Ramankutty, N. (2007). Biogeophysical effects of land use on climate: model simulations of radiative forcing and large-scale temperature change. *Agr Forest Meteorol*, *142*, 216–233.

Blum, W. E. H. (2005). Functions of soil for society and the environment. *Reviews in Environmental Science and Bio/Technology*, *4*(3), 75–79. doi:10.1007/s11157-005-2236-x

Bouma, J., Broll, G., Crane, T. a., Dewitte, O., Gardi, C., Schulte, R. P., & Towers, W. (2012). Soil information in support of policy making and awareness raising. *Current Opinion in Environmental Sustainability*, *4*(5), 552–558. doi:10.1016/j.cosust.2012.07.001

Bridges, E. M., & Oldeman, L. R. (1999). Global assessment of human-induced soil degradation. *Arid Soil Research and Rehabilitation*, *13*(4), 319–325. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0032884103&partnerID=40&md5=1c88780fc9e66d66098f7bbf119f271a

Chesworth, W. (2008). *Encyclopedia of Soil Science*. Springer. Retrieved from http://books.google.it/books?id=EOYYM0-DAGQC

Creamer, R. E., Brennan, F., Fenton, O., Healy, M. G., Lalor, S. T. J., Lanigan, G. J., … Griffiths, B. S. (2010). Implications of the proposed Soil Framework Directive on agricultural systems in Atlantic Europe - a review. *Soil Use and Management*, *26*(3), 198–211. doi:10.1111/j.1475-2743.2010.00288.x

E. A. C. Costantini, C. D. (Ed.). (2013). *THE SOILS OF ITALY*. *Land Degradation & Development* (Series Tit.). Springer Netherlands. doi:10.1007/978-94-007-5642-7

EC. (2014). Soil carbon sequestration for climate food security and ecosystem services - JRC Science ad Policy reports. EUR26540EN. In G. Halldorsson, F. Bampa, A. B. Porsteinsdottir, B. D. Sigurdsson, L. Montanarella, & A. Arnalds (Eds.), *Proceedings of the International conference 27-29 May 2013 Reykjavik Iceland* (p. 388). Brussels, Belgium: European Commission. doi:10.2788/17815

EU. (2013a). *Decision n 1386/2013/EU of the parliament and of the council of 20 november 2013 on a general Union Environment Action Programme to 2020 Living well, within the limits of our planet.* (pp. 171–200). Brussels.

EU. (2013b). REGULATION (EU) No 1305/2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 december 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) and repealing Council Regulation (EC) No 1698/2005. Brussels: Official Journal of the European Union.

EU. (2013c). REGULATION (EU) No 1306/2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 December 2013 on the financing, management and monitoring of the common agricultural policy and repealing Council Regulations (EEC) No 352/78, (EC) No 165/94, (EC) No 2799/98. Brussels: Official Journal of the European Union.

EC. (2013). REGULATION (EU) No 1307/2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 december 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation. Brussels: Official Journal of the European Union.

EC. (2012a). (COM (2010) 672 final) COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, The CAP towards 2020:Meeting the food, natural resources and territorial challen. (E. Commission, Ed.). Brussels: European Commission. Retrieved from http://ec.europa.eu/agriculture/cap-post-2013/communication/com2010-672_en.pdf

EC. (2012b). *(COM(2012)46 final) Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, The implementation of the Soil Thematic Strategy and on going activities*. (E. Commission, Ed.) (Vol. 0086). Brussels: European Commission. Retrieved from http://www.parlament.gv.at/PAKT/EU/XXIV/EU/07/22/EU_72283/imfname_10018183.pdf

EC. (2011). (COM (2011)571 final) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Roadmap to a resource Efficient Europe. *Roadmap to a Resource Efficient Europe (COM(2011) 571 Final)*. Brussels: European Commission.

EC. (2009a). (COM(2009) 147 final). White Paper. Adapting to climate change: towards a European framework for action. Brussels: European Commission.

EC. (2009b). *(SEC(2009) 417). Commission staff working document. Accompanying the White Paper, Adapting to climate change: towards a European framework for action. Adapting to climate change: the challenge for European agriculture and rural areas.* (E. Commission, Ed.). Brussels: European Commission. Retrieved from http://ec.europa.eu/agriculture/climate-change/pdf/sec2009_1093_en.pdf

EC. (2009c). *Final Report on the project Sustainable Agriculture and Soil Conservation (SoCo)* (p. 169). Office for Official Publications of the European Communities, Luxembourg: EC. Retrieved from http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/EUR23820.pdf

EC. (2006a). (COM (2006) 232) Proposal for a Directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC. Brussels: European Commission.

EC. (2006b). (COM((2006)231 final) Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee of the Regions, Thematic Strategy for Soil Protection. (E. Commission, Ed.). Brussels: European Commission. Retrieved from http://ec.europa.eu/environment/soil/pdf/com_2006_0231_en.pdf

EEA. (2010). *The European environment — state and outlook 2010: synthesis*. Copenhagen: European Environment Agency. doi:10.2800/45773

EU. (2009). *EC No 73\2009 Council Regulation establishing common rules for direct support schemes for farmers under the common agricultural policy and establishing certain support schemes for farmers, amending Regulations (EC) No 1290/2005, (EC) No 247/2* (pp. 16–99). Brussels: Official Journal of the European Union.

Faulkner, E. H. (1943). *Plowman's folly* (p. 155). New York: Grosset & Dunlap.

Freibauer, A., Rounsevell, M. D. a, Smith, P., & Verhagen, J. (2004). Carbon sequestration in the agricultural soils of Europe. *Geoderma*, *122*(1), 1–23. doi:10.1016/j.geoderma.2004.01.021

Goebel, M.-O., Bachmann, J., Reichstein, M., Janssens, I., & Guggenberger, G. (2011). Soil water repellency and its implications for organic matter decomposition - is there a link to extreme climatic events? *Global Change Biology*, *17*(8), 2640–2656. doi:10.1111/j.1365-2486.2011.02414.x

Guo, L., & Gifford, R. (2002). Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, 345–360. Retrieved from http://onlinelibrary.wiley.com/doi/10.1046/j.1354-1013.2002.00486.x/full

IPCC. (2007). *Climate Change 2007: Synthesis report. Fourth Assessment report of the IPCC, AR4.* Cambridge University Press, Cambridge. Retrieved from http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M. F., Bampa, F., van Wesemael, B., … Miglietta, F. (2014). Current status, uncertainty and future needs in soil organic carbon monitoring. *Science of the Total Environment*, *468-469*, 376–383. doi:10.1016/j.scitotenv.2013.08.026

Jandl, R., & Olsson, M. (2011). Introduction to Carbon in Sensitive European Ecosystems: From Science to Land Management. In *Soil Carbon in Sensitive European Ecosystems: From Science to Land Management* (pp. 1–12). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84888734546&partnerID=40&md5=4ed334d2c7ff70c917d059db937b5971

Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, *10*(April), 423–436. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0043272180&partnerID=40&md5=e24809836fa1e600e2c54476ca287048

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F., & Schuman, G. E. (1997). Soil quality: A concept, definition, and framework for evaluation: (A guest editorial). *Soil Science Society of America Journal*, *61*(1), 4–10. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0031285130&partnerID=40&md5=52a098f4cdf9cd6bd6a5a12dbf64e8b2

Kätterer, T., Andrén, O., & Persson, J. (2004). The impact of altered management on long-term agricultural soil carbon stocks – a Swedish case study, 179–187.

Kibblewhite, M. G., Miko, L., & Montanarella, L. (2012). Legal frameworks for soil protection: Current development and technical information requirements. *Current Opinion in Environmental Sustainability*, *4*(5), 573–577. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84869152254&partnerID=40&md5=6cccf877e2b1a4ae94d8a6154995914f

Korschens, M., Weigel, A., & Schulz, E. (1998). Turnover of soil organic matter (SOM) and long-term balances - Tools for evaluating sustainable productivity of soils. *Zeitschrift Fur Pflanzenernahrung Und Bodenkunde*, *161*(4), 409–424. Retrieved from <Go to ISI>://WOS:000075580900008

Lal, R. (2011). Sequestering carbon in soils of agro-ecosystems. *Food Policy*, *36*(SUPPL. 1), S33–S39. doi:10.1016/j.foodpol.2010.12.001

Lal, R. (2010b). Beyond Copenhagen: Mitigating climate change and achieving food security through soil carbon sequestration. *Food Security*, *2*(2), 169–177. doi:10.1007/s12571-010-0060-9

Lal, R. (2010a). Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *BioScience*, *60*, 708–721. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-77957958203&partnerID=40&md5=e4df595790bd22a0f01d25f11886508e

Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation and Development*, *17*(2), 197–209. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-33646052865&partnerID=40&md5=86e39e12bcbc0f2043a2b4af1e9778ff

Lal, R. (2004a). Carbon emission from farm operations. *Environment International*, *30*(7), 981–990. doi:10.1016/j.envint.2004.03.005

Lal, R. (2004b). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*(5677), 1623–1627. doi:10.1126/science.1097396

Lal, R. (2004c). Soil carbon sequestration to mitigate climate change. *Geoderma*, *123*(1-2), 1–22. doi:10.1016/j.geoderma.2004.01.032

Lal, R., & Greenland, D. J. (1979). Soil physical properties and crop production in the tropics. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0018585495&partnerID=40&md5=0e0bb1bac00ab6b0cedcd02000014579

Loveland, P., & Webb, J. (2003). Is there a critical level of organic matter in the agricultural soils of temperate regions: A review. *Soil and Tillage Research*, *70*(1), 1–18. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0037371256&partnerID=40&md5=c01505a9ee24797de3520c96aa8042fe

Midgley, G. F., Bond, W. J., Kapos, V., Ravilious, C., Scharlemann, J. P. W., & Woodward, F. I. (2010). Terrestrial carbon stocks and biodiversity: Key knowledge gaps and some policy implications. *Current Opinion in Environmental Sustainability*, *2*(4), 264–270. doi:10.1016/j.cosust.2010.06.001

Montanarella, L., & Vargas, R. (2012). Global governance of soil resources as a necessary condition for sustainable development. *Current Opinion in Environmental Sustainability*, *4*(5), 559–564. doi:10.1016/j.cosust.2012.06.007

Olson, K. R. (2013). Soil organic carbon sequestration, storage, retention and loss in U.S. croplands: Issues paper for protocol development. *Geoderma*, *195-196*, 201–206. doi:10.1016/j.geoderma.2012.12.004

Olson, K. R. (2010). Impacts of tillage, slope, and erosion on soil organic carbon retention. *Soil Science*, *175*(11), 562–567. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-78649367747&partnerID=40&md5=561ae7bb511d9d65722400da62115d1a

Parton, W. J., Ojima, D. S., Cole, C. V, & Schimel, D. S. (1994). A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. *Quantitative Modeling of Soil Forming Processes. Proc. Symposium, Minneapolis, 1992*, 147–167. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0028571355&partnerID=40&md5=4695411a20a0ea2da8aeb318bd767f57

Paul Obade, V. De, & Lal, R. (2013). Assessing land cover and soil quality by remote sensing and geographical information systems (GIS). *Catena*, *104*, 77–92. doi:10.1016/j.catena.2012.10.014

Powlson, D. S., Whitmore, a. P., & Goulding, K. W. T. (2011). Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. *European Journal of Soil Science*, *62*(1), 42–55. doi:10.1111/j.1365-2389.2010.01342.x

Reeves D. W. (1997). Reeves_1997_The role of soil organic matter in maintaining soil quality in continuous cropping systems.pdf. *Soil and Tillage Research*, *43*.

Schils, R. (2008). *Review of existing information on the interrelations between soil and climate change (CLIMSOIL) – Final Report. Contract number 70307/2007/486157/SER/B1:208.* (R. (ed) Schils, Ed.). Brussels: European Commission. Retrieved from http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/climsoil_report_dec_2008.pdf

Schlesinger, W. H. (1997). *Biogeochemistry: an analysis of global change*. *Academic Press*. San Diego, Calif: Academic Press.

Schulte, R. P. O., Creamer, R. E., Donnellan, T., Farrelly, N., Fealy, R., O’Donoghue, C., & O’hUallachain, D. (2013). Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. *Environmental Science and Policy*. doi:10.1016/j.envsci.2013.10.002

Schwilch, G., Hessel, R., & Verzandvoort, S. (2012). *Desire for Greener Land. Options for Sustainable Land Management in Drylands.* (V. S. Schwilch, G., R. Hessel, Ed.) (WOCAT.). Bern, Switzerland, and Wageningen, The Netherlands: University of Bern - CDE, Alterra - Wageningen UR, ISRIC - World Soil In□ormation and CTA - Technical Centre □or Agricultural and Rural Cooperation. : Bern, Switzerland, and Wageningen, The Netherlands: University of Bern - CDE, Alterra - Wageningen UR, ISRIC - World Soil Information and CTA - Technical Centre for Agricultural and Rural Cooperation.

Seybold, C. a., Herrick, J. E., & Brejda, J. J. (1999). Soil Resilience: a Fundamental Component of Soil Quality. *Soil Science*, *164*(4), 224–234.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., … Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 789–813. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-40949120517&partnerID=40&md5=67f5dcd5ae9ef346f2a330cdf2b81294

Smith, P., Smith, J. U., Franko, U., Kuka, K., Romanenkov, V. A., Shevtsova, L. K., … Lisovoi, N. V. (2007). Changes in mineral soil organic carbon stocks in the croplands of European Russia and the Ukraine, 1990-2070; Comparison of three models and implications for climate mitigation. *Regional Environmental Change*, *7*, 105–119. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-34250872776&partnerID=40&md5=27bb14014ecfd19a0c56ad81bf9ca6b7

Smith, P. (2004). Monitoring and verification of soil carbon changes under Article 3.4 of the Kyoto Protocol. *Soil Use and Management*, *20*(SUPPL.), 264–270. doi:10.1079/SUM2004239

Smith, P., Powlson, D. S., Glendining, M. J., & Smith, J. U. (1997). Potential for carbon sequestration in European soils: Preliminary estimates for five scenarios using results from long-term experiments. *Global Change Biology*, *3*(1), 67–79. Retrieved from http://onlinelibrary.wiley.com/doi/10.1046/j.1365-2486.1997.00055.x/abstract

Soderstrom, B., Hedlund, K., Jackson, L., Katterer, T., Lugato, E., Thomsen, I., & Bracht Jorgensen, H. (2014). What are the effects of agricultural management on soil organic carbon (SOC) stocks? *Environmental Evidence*, *3*(1), 2. Retrieved from http://www.environmentalevidencejournal.org/content/3/1/2

Stockmann, U., Adams, M. a., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., … Zimmermann, M. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems and Environment*, *164*(2013), 80–99. doi:10.1016/j.agee.2012.10.001

UN. (1997). KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE. Retrieved from http://www.unfccc.int

UNFCCC. (1992). United Nations General Assembly. United Nations Framework Convention on Climate Change. http:// www.unfccc.int/resources. (U. N. UNFCCC, Ed.). New York.

Van-Camp, L., Bujarrabal, B., Gentile, A. R., Jones, R. J. A., Montanarella, L., Olazabal, C., … Van-Camp L. A.R. Gentile, R.J.A. Jones, L. Montanarella, C. Olazabal, S-K. Selvaradjou, B. B. (2004). *Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection.* (p. 872). Office for Official Publications of the European Communities, Luxembourg.: EC. Retrieved from http://ec.europa.eu/environment/soil/pdf/vol5.pdf

Veneto, R. (2011). *Rapporto Statistico 2011*. Retrieved from http://statistica.regione.veneto.it/ENG/Pubblicazioni/RapportoStatistico2011/index.html

Verheijen, F. G. a, Jones, R. J. a, Rickson, R. J., & Smith, C. J. (2009). Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews*, *94*(1-4), 23–38. doi:10.1016/j.earscirev.2009.02.003

Zdruli Jones, R.J.A. and Montanarella, L, P. (2004). *Organic Matter in the Soils of Southern Europe. European Soil Bureau Technical Report, EUR 21083 EN* (p. 16). Office for Official Publications of the European Communities, Luxembourg: European Commission. Retrieved from http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/esb_rr/n15_OMsouthEurope.pdf

Chapter II

EU soil database comparison: EIONET vs. OCTOP and the Veneto and Trentino Alto Adige case studies

Introduction

SOC content is monitored within the EU Member States (MSs) at national/regional/local levels by soil science institutes and other soil related organizations. But at EU level all the information available on SOC are hosted by the European Soil Data Centre (ESDAC). ESDAC is a thematic platform for soil data established in 2005 by the EC and the European Environment Agency (EEA)(Panagos *et al.*, 2012).

As regard to SOC the data actually available in ESDAC come from three different sources:

a) OCTOP
b) LUCAS soil survey 2009.
c) EIONET

The geographical distribution of the SOC content at EU level has been mapped for the first time by Jones *et al.*, (2005) creating the map of topsoil organic carbon (OC) content known as OCTOP. At the present time OCTOP represents the most homogeneous and comprehensive data on the OC content in EU soils and can be extracted from the European Soil Database (ESDB), at a scale of 1:1,000,000, in combination with associated databases on land cover, climate and topography. This modelled map is currently used by policy makers and scientific communities as an input for developing strategies for soil protection and in climate change modelling, agriculture and other environmental domains.

LUCAS soil survey started in 2009 and represents the first harmonized soil monitoring system at EU level; LUCAS will be discussed in chapter IV. Before LUCAS there were no homogeneous spatial SOC estimates at EU scale based on data coming from soil monitoring networks. The only data available are limited in monitoring sites per country, in density of samples and the final the estimates on SOC content and stocks rely on various assumptions (Saby *et al.*, 2008; Jandl *et al.*, 2014).

The European Environment Information and Observation NETwork (EIONET) consists of representative organizations from 38 European countries (including the 27 MS of the EU plus other European countries). The network is built on national focal points that co-ordinate primary contact points and national reference centres for specific areas. Its aim is to provide timely and quality-assured data, information and expertise to assess the state of the environment in Europe, and the pressures acting upon it. In 2005 it has been decided that all the soil data and activities carried out by EEA in collaboration with EIONET are hosted in ESDAC-JRC. At that time the Directorate General for the Environment (DG ENV) and EEA have identified the decline in SOM and soil erosion as urgent policy priorities to be addressed by the collection of EU soil data.

JRC, in this regards, decided to perform in 2010 a soil data collection exercise through the EIONET network among MS. The objective was to create a EU wide dataset for SOC and soil erosion indicators according to a grid based approach (Panagos *et al.*, 2013a).

This first chapter refers to the work done in the Joint Research Centre – ESDAC platform and specifically to the paper from Panagos *et al.*, (2013a) and aims to describe briefly the SOC data collected through the EIONET network, the comparison with the modelled OCTOP data and the Veneto Region case study.

Materials and methods

EIONET-SOIL network consists of 33 member countries of the EEA which includes the 28 MS of the EU plus Iceland, Liechtenstein, Norway, Switzerland and Turkey (the six Western Balkan countries - Albania, Bosnia and Herzegovina, the former Yugoslav Republic of Macedonia, Montenegro, Serbia and Kosovo - are defined as cooperating countries). The network is built on National Focal Points (NFPs) that co-ordinate Primary Contact Points (PCPs) and National Reference Centres (NRCs). The EIONET member countries have no legal obligation to participate and both PCPs and NRCs for soil contribute on a voluntary basis on the data collection.

In cooperation with the EIONET-SOIL network, the ESDAC adopted a data collection protocol on the basis of a standard grid of 1km x 1km cells that was assigned to each country. For each cell the countries had to provide their best possible (estimated or measured) information on SOC content and soil erosion pertaining to that cell. The grid of cells selected covering the whole European territory follows the specifications suggested by the INSPIRE Directive (EU, 2007).

The data collection exercise was performed by ESDAC in 2010 and the objective was to create a grid based pan-European dataset for SOC.

In order to enable a comparative analysis for the correct interpretation of the cell values, the information collected by the participating countries included the accompanying metadata. The following metadata for SOC were requested: 1) the period of the ground survey(s); 2) the method used for a spatial interpolation of point data; 3) the land use types covered. Land use is a major factor in defining the SOC content, its definition has been left to the member countries. Other information on the SOC data such as the sampling method of organic layers or the measurement method used to determine SOC and bulk density (BD), were generally not included in the metadata received.

As regard to the SOC amount, EIONET-SOIL member countries have been asked to express the cell values of OC in tonnes per hectare (t ha^{-1}) and in the percentage (%) of SOC content in the cell, both for the same depth range of 0-30cm.

Results and Discussion

For the SOC content in percentage, 12 EIONET countries provided data (32 percent of total EIONET-SOIL network); out of these 12 only 5 countries provided data for more than 50 percent of their geographical coverage, in some cases for all land uses while for others, only for agricultural soils (e.g. Austria and Slovakia). Also Estonia provided data covering 28% of the country but only for the 0-20 cm depth. The information on metadata collected can be found in table 2.1.

Table 2.1 EIONET-SOIL metadata collected for SOC (0-30 cm) (Panagos *et al.*, 2013a).

Country	*Number of 1km cells*	*Area Coverage SOC value (%)*	*Average SOC (%)*	*Survey period*	*Method*	*Land use covered*
Austria	55,329	64.8	2.7	1970s	kriging	Agricultural
Bulgaria	14,101	12.6	2.1	2004-2008	No interpolation.	Agricultural
Denmark	42,917	100.0	2.0	2000s	45,000 points interpolated kriging in 250m x 250m cell.	all land areas
Estonia	13,379	28.4	3.5	2002-2010	Near Infrared Reflectance Spectroscopy (NIRS).	Agricultural
Ireland	1,322	1.8	13.3	not specified	No interpolation.	Agricultural
Italy	30,521	10.0	3.1	1991-2006	two regions in northern Italy	Non-urban areas.
Netherlands	29,866	77.3	3.5	1989-2000	selection of sites	Agricultural
Norway	14,249	4.1	3.2	not specified	not specified	Agricultural
Poland	220,090	70.1	2.6	Mid 1990s	extrapolation to polygon from point data	Agricultural
Serbia	1,181	1.3	2.0	not specified	no interpolation	Agricultural
Slovakia	26,959	54.0	1.3	1961- 1970	spatial interpolation	Agricultural
Switzerland	105	0.3	4.5	not specified	no interpolation	Agricultural

The metadata, partly presented in Table 2.1, showed that the countries are using various methodologies for soil surveying and data collection. In some cases (e.g. Austria and Slovakia) the data were collected more than 30 years ago and only for agricultural areas. Only The Netherlands provided the full coverage. Despite being derived from different data sources, the collected data have been harmonized to account for different methods of soil analyses, scales and time periods. Figure 2.1 shows the distribution of the EIONET-SOIL SOC content data.

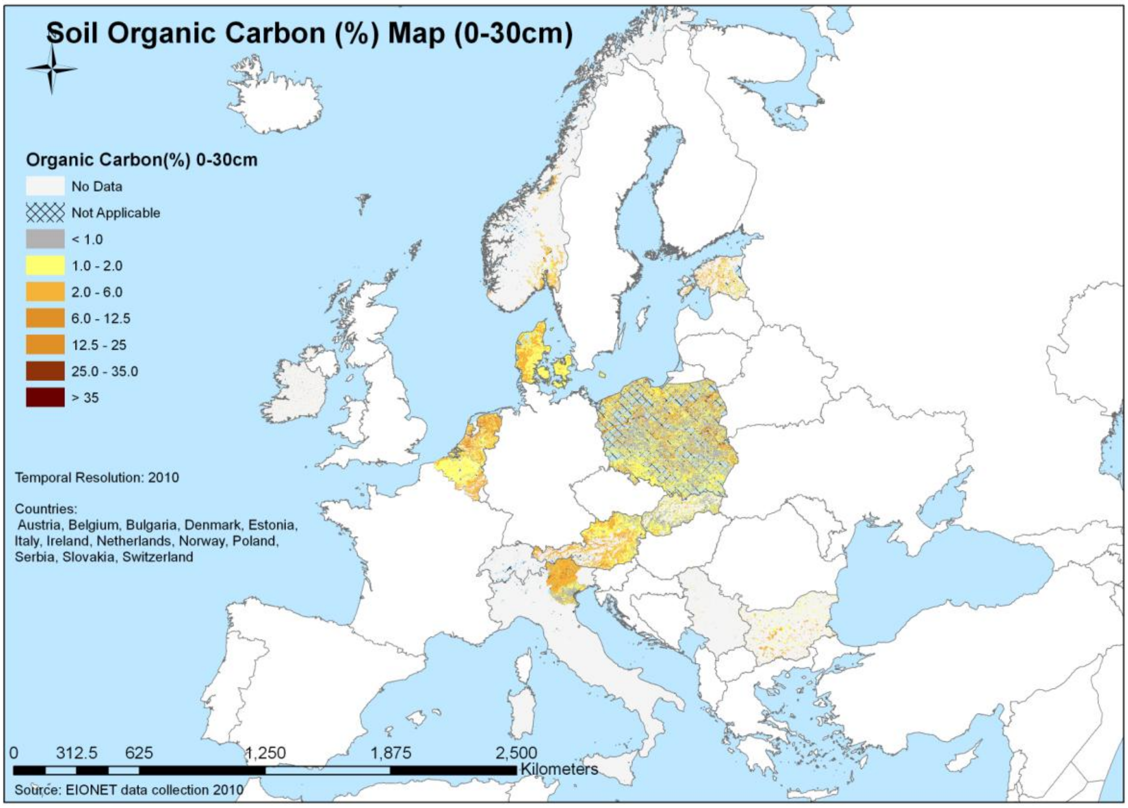


Figure 2.1 EIONET SOC map 0-30 cm (Panagos *et al.*, 2013a)

This results were compared with the modelled European SOC data of OCTOP (Jones *et al.*, 2005a). Where the SOC was reported for a specific LUC type (e.g. agricultural land), a corresponding thematic layer could be derived

From the presence of SOC in the grid cell or from the proportion reported in the metadata. If the land use proportion was not reported for the grid cell the thematic layer was not derived. However the SOC has been still compared with the OCTOP in cases where the latter land use coincides with the land use of the EIONET-SOIL grid. The two land use layers compared showed differences in the spatial distribution. The differences could be reduced by using a common land use layer for both data sets but most of the data collected by EIONET-SOIL were based on agricultural land. For this reason has been derived a layer from OCTOP combining the classes “Cultivated” and “Managed Grassland”.

The comparison revealed that the SOC (%) in the average modelled OCTOP dataset values were almost double than in the collected EIONET-SOIL data in North-East and Central Europe. For the two regions of Italy both modelled and EIONET-SOIL datasets were quite close (Panagos *et al.*, 2013a).

While the estimates derived from the countries used a variety of different approaches, the method used to generate the OCTOP estimates is based on soil properties data hosted in the ESDB and on the pedo-transfer rule (PTR) 21 of the ESDB (King *et al.*, 1994) which has been developed by Van Ranst *et al.*, (1995). The OCTOP data were validated using measured SOC data coming from England/Wales and Italy soil samples.

The reasons that could lead to these differences are: difference due to peat classification and subsequent PTRs conditions (e.g. in Netherlands and Poland, the difference is explained due to peats which have been drained in the last 20-30 years); difference due to geo-statistical mapping analysis; difference due to conditions of PTR selected (e.g. in Denmark, Austria and Slovakia, the PTR of the model OCTOP had as output much higher SOC values than the ones provided by the countries). The possible overestimation of the SOC levels in the OCTOP could be due to the input data deriving from the ESDB initially collected prior to 1980; this data may reflects land use patterns that are significantly different to current conditions.

As regard to the SOC stocks, estimates were provided from 6 participating countries: Bulgaria with 315 Tg of C for the 0-25 cm; Denmark with 370 Tg (but for only 10 grid cells located on the island Ronne); Netherlands with 299 Tg (77% coverage); Poland with 1,753 Tg (70% coverage) and Slovakia with 122 Tg (54% coverage) in Table 2.1. Italy provided full coverage information on SOC stocks for 10 regions, the estimate was 994 Tg.

Table 2.2 SOC stocks for EIONET-SOIL.

Country	*Number of 1km cells*	*Area Coverage SOC value (%)*	*Mean OC (t C ha^{-1}) (0-30cm)*	*SOC stock (Tg)*
Bulgaria	112,324	100	28	315,2
Denmark	42,917	100	86,4	370,6
Italy	176,491	57,6	56,3	993,9
Netherlands	29,866	77,3	100,1	298,8
Poland	220,090	70,1	79,6	1752,7
Slovakia	26,959	54	45,3	122,3

A literature review on these countries has been done to evaluate the data collected. The total SOC stock in the top layer 0–30cm for The Netherlands covering approximately 90% of the country area is calculated to be 286 Tg C (Kuikman *et al.*, 2003). The SOC stocks in Denmark varies from 563 to 598 Tg C, with 579 Tg C as the average when urban areas, lakes and open fjords are excluded (Krogh *et al.*, 2003), while in EIONET-SOIL are 371 Tg and 596 Tg in OCTOP. For Italy, SOC stocks in the top 30cm of mineral soil for croplands was estimated by Chiti *et al.*, (2012) to be 490.0±121.7 Tg C (with a confidence level of 95%).

The SOC stocks were also compared with the calculation based on the OCTOP dataset. In this case the comparison was based on common land use mask or adjustment of the OCTOP land use layer to the land use of EIONET-SOIL. The common mask was generated only for the grid cells where both EIONET-SOIL and OCTOP land use had the same land use.

OCTOP estimates the SOC stock of the EU (0-30 cm) about 73 Gt, of which 30% (around 22 Gt C) is associated with agricultural soils: 15-17% (around 13 Gt C) by croplands and 12% (around 8 Gt C) by pasture (Jones *et al.*, 2005a). Analysis suggests that the share of arable land cover in the OCTOP layer is overestimating this land use when compared with statistics coming from DG EUROSTAT. Figures coming from EUROSTAT – CLC classes for the extent of agricultural areas date 2010-11 while OCTOP database has a baseline referring to 1990. In the OCTOP layer, arable land occupies approximately 1/3 (32.7%) of the land area, while for the 2010-11 statistics, the share of arable land on the land area is closer to ¼ (24.5%). Given that the share of SOC stocks on arable land for 1990 is 17.4% and that EUROSTAT data show that the area of arable land decreased from 1990, the share of SOC stocks on cropland is more likely around 15% of the total SOC stock for EU-26.

The mean OCTOP estimates of SOC content are generally higher than the national data from EIONET-SOIL.

The OCTOP and EIONET-SOIL data match very well for the Trentino Alto Adige Region and Veneto region in Italy. For The Netherlands, the analysis has been performed separately for soils where peatlands covers more than 95% of the units derived from ESDB and for soils where peat is less than 10% of the units. The influence of treating areas of peat is high.

The Veneto Region case study

Veneto region has, reflecting its climate and pedology, naturally low values of OC if compared with the EU standards and averages. Croplands, following ARPAV source[17] in Figure 2.2, have 1.5-2% of SOM, less than 40 t ha^{-1}, considered normal values at regional level. High values, mainly in the upper High plain, could be due to the widespread livestock sector that assures regular organic input into the soil.

It interesting to note that following Loveland & Webb, (2003) there is a positive relationship between aggregate stability and SOM, but there is no effect on structural stability below a threshold value of 2%. Soils with higher level of OC have a desirable structure that tends to crumble and break apart easily and is more suitable for crop growth than hard, cloddy structures.

The data for the EIONET-SOIL were provided by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA). The data were provided only for two regions Trentino-Alto Adige and Veneto, equal to 10% of the whole country.

The data were collected in the rage of years 1991–2006.

[17] www.arpa.veneto.it/suolo

For these two regions the spatial coverage within the geographic areas is fairly complete and the data pattern very similar to OCTOP ones (Fig. 2.3).

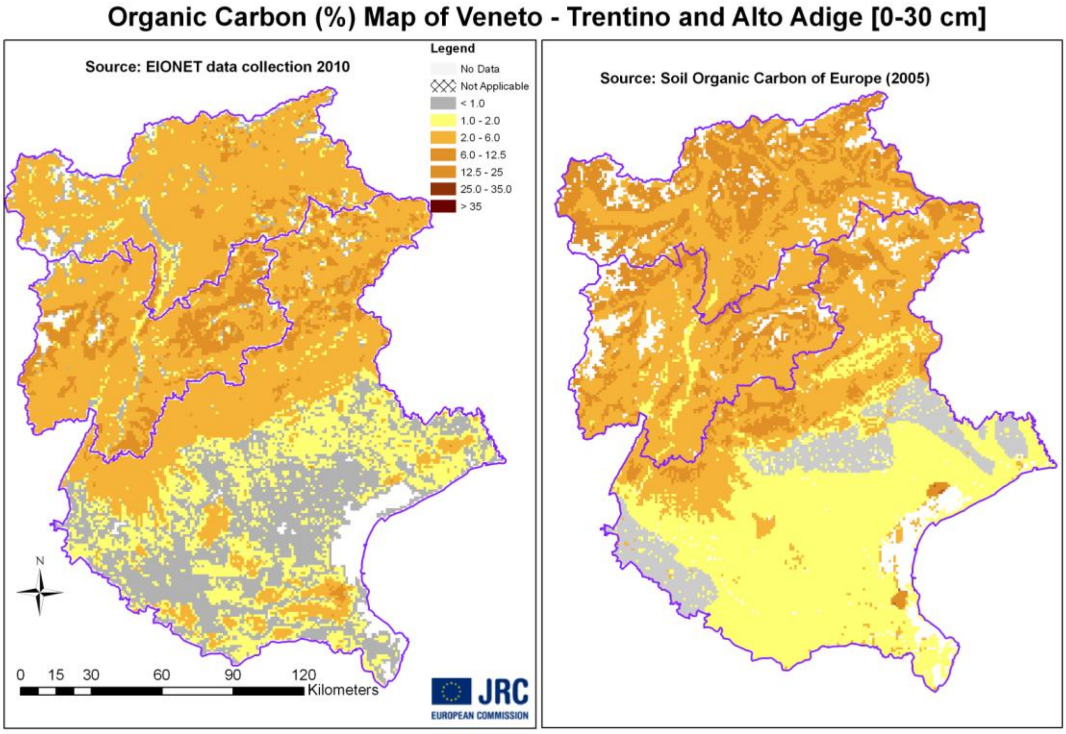


Figure 2.2 SOC (%) map from EIONET on the left and from OCTOP on the right for Trentino Alto Adige and Veneto Region (Panagos *et al.*, 2013a).

For Veneto Region the mean of SOC content (%) was 2.2 (max 10.5 and Standard deviation 1.8) and for OCTOP 2.3 (max 19 and Standard deviation 1.9)

The overall results suggested that the current estimates of SOC Stock in Europe in the topsoil could be much less than the 73-79 Pg, as reported by Schils (EC 2008). OCTOP data provide a good overview for Europe but it could be improved through the integration of SOC data that originate directly from European countries and reflect the actual situation of topsoil SOC. In addition, the harmonized national data could potentially be used as a support for the revision of the existing method (PTR21) that formed the basis of the OCTOP data, especially for the geographic areas where the provided EIONET-SOIL data covers a region or soil type which was not included when defining the PTR21.

Conclusions

EIONET-SOIL network is one of the first examples of an organized official network for soil monitoring data purpose in Europe where countries participated by submitting spatial data on SOC to a centralized data centre, ESDAC. As regards to the collection of SOC data is the first attempt between EU and not EU MSs to submit spatial information data. Also soil erosion has been collected as indicator in the same framework. The data showed how the methods in estimating SOC values were different. However having positive feedback from EIONET-SOIL member countries through ESDAC platform is a good starting point for a future data collection (i.e. many of the available datasets at national level across Europe have not been accessed yet) or for creating a framework for reporting for soil at the EU level. EIONET-SOIL network could potentially become a monitoring network, able to detect SOC changes over a certain period (e.g. in 10-years´ time). This collection, even if fragmented, represents the best "picture" possible that can be achieved through national data collection at European extension. On the other side OCTOP remains the most homogeneous and complete SOC dataset available in Europe.

Generally there are difficulties in getting data on SOC, but improvement in data availability and data quality over the years can be observed. The exercise revealed the scattered situation for SOC data in EU, but the same exercise could be done for the rest of soil threats recognised by the former Soil Thematic Strategy (EC, 2006a).

OCTOP has been validated by two soil data surveyed : Italian (agricultural land only) and UK soil data, for which it was found to be well matched (Jones *et al.*, 2005b). EIONET-SOIL confirms the validation for Italy dataset which has similar patterns and values as the OCTOP data. However for the other countries the estimates in OCTOP seems to be higher in SOC content compared to EIONET-SOIL, for this reason the current figure of 73–79 Pg SOC stock in Europe in the topsoil could be too positive (Panagos *et al.*, 2013a).

The EIONET-SOIL data demonstrated also its potentiality for the revision of some of the OCTOP modelling options for certain parts of Europe, such as the PTR21. However the comparison was uncertain for the spatial distribution of the EIONET-SOIL data on agricultural and forest land, for the different depth assessed, for the influence of peat accounted or not and for the time scale of the data collected. The metadata proved to be extremely important for the interpretation of EIONET-SOIL data during the evaluation and during the comparison even though the data collected were neither complete nor homogeneous due to different methods, analysis and spatial extrapolation (Panagos *et al.*, 2013a; Lugato *et al.*, 2014a).

Acknowledgements

This chapter is largely based on the work done in the contest of EIONET project[18].

References

Chiti, T., Gardin, L., Perugini, L., Quaratino, R., Vaccari, F. P., Miglietta, F., & Valentini, R. (2012). Soil organic carbon stock assessment for the different cropland land uses in Italy. *Biology and Fertility of Soils*, *48*(1), 9–17. doi:10.1007/s00374-011-0599-4

EC. (2006). (COM((2006)231 final) Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee of the Regions, Thematic Strategy for Soil Protection. (E. Commission, Ed.). Brussels: European Commission. Retrieved from http://ec.europa.eu/environment/soil/pdf/com_2006_0231_en.pdf

EU. (2007). *Directive 2007/2/EC of the European Parliament and of the Council (14 March 2007): Establishing An Infrastructure for Spatial Information in the European Community (INSPIRE). Directive 2007/2/EC of the European Parliament and of the Council (14 March 2007): Establishing An Infrastructure for Spatial Information in the European Community (INSPIRE)*. Brussels.

Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M. F., Bampa, F., van Wesemael, B., … Miglietta, F. (2014). Current status, uncertainty and future needs in soil organic carbon monitoring. *Science of the Total Environment*, *468-469*, 376–383. doi:10.1016/j.scitotenv.2013.08.026

Jones, R. J. a., Hiederer, R., Rusco, E., & Montanarella, L. (2005a). Estimating organic carbon in the soils of Europe for policy support. *European Journal of Soil Science*, *56*(5), 655–671. doi:10.1111/j.1365-2389.2005.00728.x

Jones, R. J. a., Hiederer, R., Rusco, E., & Montanarella, L. (2005b). Estimating organic carbon in the soils of Europe for policy support. *European Journal of Soil Science*, *56*(5), 655–671. doi:10.1111/j.1365-2389.2005.00728.x

King, D., Daroussin, J., & Tavernier, R. (1994). Development of a soil geographic database from the Soil Map of the European Communities. *Catena*, *21*(1), 37–56. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-38149145042&partnerID=40&md5=8b2c561c15258b4ed1ab9443d6ffd93d

Krogh, L., Noergaard, A., Hermansen, M., Greve, M. H., Balstroem, T., & Breuning-Madsen, H. (2003). Preliminary estimates of contemporary soil organic carbon stocks in Denmark using multiple datasets and four scaling-up methods. *Agriculture,*

[18] http://eusoils.jrc.ec.europa.eu/library/data/eionet/DataCollection.htm

Ecosystems and Environment, *96*(1-3), 19–28. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0038684588&partnerID=40&md5=d577770c82f51c1bcc1ccf83de561c6a

Kuikman, P. J., de Groot., W. J. M., Hendriks, R. F. A., Verhagen, J., & de Vries, F. (2003). *Stocks of C in Soils and Emissions of CO2 from Agricultural Soils in The Netherlands.* . (561 Alterra-Report 41., Ed.). Alterra, Wageningen. Retrieved from http://www.greenhousegases.nl/docs/AlterraRapport561.pdf

Loveland, P., & Webb, J. (2003). Is there a critical level of organic matter in the agricultural soils of temperate regions: A review. *Soil and Tillage Research*, *70*(1), 1–18. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0037371256&partnerID=40&md5=c01505a9ee24797de3520c96aa8042fe

Lugato, E., Panagos, P., Bampa, F., Jones, A., & Montanarella, L. (2014). A new baseline of organic carbon stock in European agricultural soils using a modelling approach. *Global Change Biology*, *20*(1), 313–26. doi:10.1111/gcb.12292

Panagos, P., Hiederer, R., Van Liedekerke, M., & Bampa, F. (2013). Estimating soil organic carbon in Europe based on data collected through an European network. *Ecological Indicators*, *24*, 439–450. doi:10.1016/j.ecolind.2012.07.020

Panagos, P., Van Liedekerke, M., Jones, A., & Montanarella, L. (2012). European Soil Data Centre: Response to European policy support and public data requirements. *Land Use Policy*, *29*(2), 329–338. doi:10.1016/j.landusepol.2011.07.003

Saby, N. P. a., Bellamy, P. H., Morvan, X., Arrouays, D., Jones, R. J. a., Verheijen, F. G. a., … Simota, C. (2008). Will European soil-monitoring networks be able to detect changes in topsoil organic carbon content? *Global Change Biology*, *14*(10), 2432–2442. doi:10.1111/j.1365-2486.2008.01658.x

Van Ranst, E., Vanmechelen, L., Thomasson, A. J., Daroussin, J., Hollis, J. M., Jones, R. J. A., … King, D. (1995). Elaboration of an extended knowledge database to interpret the 1:1,000,000 EU Soil Map for environmental purposes. *European Land Information Systems for Agro-Environmental Monitoring*.

Chapter III

META ANALYSIS on SOC farming options in the EU

Introduction

Land use change and land management have a notable impact on C pools and reflect GHG emissions towards climate change. While conversion of grassland, forests and peatlands to cropland determines losses of CO_2 (the FAO estimates that land use change is responsible for about one-third of global GHG emissions (FAO, 2001; Lal, 2011b), improved agricultural practices can lower CO_2 losses, storing SOM. This process known as **sequestration** can retain C in the soil from the short-term to the long-term (e.g. millennia), but it remains unknown the reason as to why some pools persists more than others and this makes it difficult to predict how soils will respond to climate change (Olson, 2010; Schmidt *et al.*, 2011).

In Europe, croplands are estimated to be the largest source of C losses released to the atmosphere each year, but this is the most difficult of all land-use types to estimates. According to Smith & Falloon, (2005), European croplands were estimated to lose 300 Tg C yr^{-1}, with the mean figure for the EU-15 estimated to be 78 Tg C yr^{-1}. Furthermore, the biological potential for C storage in the EU-15 croplands is of the order of 90-120 Tg C yr-1. The sequestration potential, considering only constraints on land use, amounts of raw materials and available land, is up to 45 Tg C yr^{-1} (Freibauer *et al.*, 2004; Smith & Falloon, 2005).

The challenge for the EU in future years, in order to ensure food security and soil quality, will be to promote sustainable management practices able to maintain the same level of agricultural production while adapting to climate change and sequestering C (Lal *et al.*, 2007; Smith *et al.*, 2007b; EC, 2009c; Lal, 2010c; Powlson *et al.*, 2011a; White *et al.*, 2012; Schulte *et al.*, 2013).

A *Best Management Practice* (BMP) defines a farming method and operations that assure optimum plant growth and minimise adverse environmental and human effects protecting the ecosystem quality (USDA, 2011). With respect to soil fertility, management practices drive SOC dynamics depending on climate, soil properties, landscape position, vegetation cover (Lal, 2008a; Schils, 2008). The **rate of SOC sequestration** follows a sigmoid curve and is represented by the slope of the curve *Dy/Dx* in Figure 3.2. The adoption of a recommended management practice could raise the SOC pool to a new equilibrium level generally lower than the antecedent pool under natural conditions.

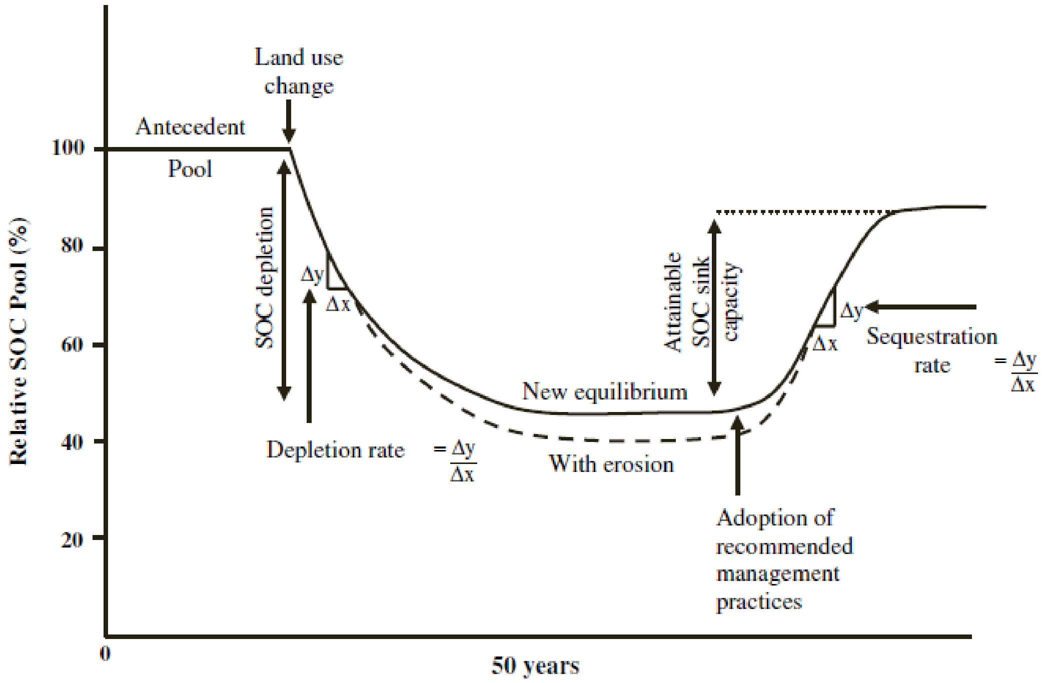


Figure 3.1 - The SOC depletion process due to land use conversion from natural to agricultural ecosystem.

The rate of SOC sequestration depends *inter alia* on soil type, topography, land use, climate and management such as cultivation practices, type of plant/crop cover, soil drainage status, etc. (Davidson & Janssens, 2006; Lal, 2008b; Creamer *et al.*, 2010b). The main management practices in agricultural soils could be grouped in : tillage techniques (i.e. reduced/minimum tillage or zero tillage), soil application (i.e. manure, crop residues, compost, improved fertilizations, biochar application), cropping systems (i.e. cover and deep-rooting crops, improved rotations, improved irrigations), land conversion (i.e. to grassland/peatlands/woodland)(Kimble R. Lal, Follet R., 2002; Lal, 2004a, 2004d; Campbell *et al.*, 2005). Many studies and report in many parts of the world have investigated the **potential** of such measures (Kimble R. Lal, Follet R., 2002; Lal, 2004d; IPCC, 2007; Lal *et al.*, 2007; Schils, 2008; EC, 2009a; Gobin P. Campling, L. Janssen, N. Desmet, H. van Delden, J. Hurkens, P. Lavelle and S. Berman, 2011; Delgado *et al.*, 2013; Stavi & Lal, 2013; Venkateswarlu *et al.*, 2014). Long-term field experiments (LTE) have been implemented to monitor SOC dynamics and investigate the effects of a practice on the C pool (Kätterer & Kirchmann; Morari *et al.*, 2006), but due to several uncertainties still more pertinent research on quantitative aspects is needed (Stockmann *et al.*, 2013).

Various meta-analysis have been assessed focusing on a single practice: in McSherry & Ritchie (2013), a review on grazing effect; in Aguilera *et al.*, 2013 a review on organic management and other combined practices in Mediterranean croplands; in Don *et al.*, 2011 and in Guo & Gifford, 2002 a review of land use change; in Hoogmoed *et al.*, 2012 on the afforestation of pastures; in Jeffery *et al.*, 2011 on the biochar application; in Seufert *et al.*, 2012 and in Tuomisto *et al.* (2012) on organic agriculture; in VandenBygaart *et al.*, 2003 a compendium on Canadian agricultural soils; in (Van den Putte *et al.*, 2010) on Conservation Agriculture; in Reeves, 1997 on continuous cropping experiments; in Delgado *et al.*, (2011) on conservation practices in US.

This chapter focuses a meta-analysis on the **management practices and measures** applied in the EU agricultural soils and ability to maintain or increase the level of SOC stocks following two main strategies: increasing/adding C inputs or decreasing soil disturbance (Lal, 2004d; Alluvione *et al.*, 2013). The additional benefits include improving soil and water quality, biodiversity, reducing erosion, improving fertility and crop production.

The objective is to assess their quantitative bio-chemical **potential** as possible **mitigation options** in cropland and grassland to sequester SOC. On the basis of this assessment, a limited number of **alternative** management practices (AMPs) have been selected for understanding the model accuracy and simulating the selected AMPs in chapter 4.

The work showed in this chapter has been implemented under the CAPRESE project[19]. Information on the management practices are described in report of Task1 and the meta-analysis belongs to Task3.

---

[19] http://eusoils.jrc.ec.europa.eu/library/Themes/SOC/CAPRESE/ and http://mars.jrc.ec.europa.eu/mars/Projects/CAPRESE

Materials and methods

A literature research has been done focusing on two main sources: scientific peer reviewed papers and institutional EU reports on the management practices and measures applied in agricultural soils with potential to sequester SOC, because of their significant role for food production in the EU. At the very beginning the management practices have been defined, this is part of Task1 of CAPRESE project and will not be listed in this chapter.

The literature review has been done through the major scientific search platforms available (e.g. SciVerse – ScienceDirect, Scopus-, Web of Knowledge, Wiley Online Library, SpringerLink), the library at disposal in the EUSOIL website, DG JRC library and SOIL Action library.

The options taken into consideration in the scientific literature have been assessed on a broad range of experiences, on the following criteria for the selection:

a) Geographically representative
   - EU climate (cool mild climate): precipitation, temperature, in a temperate life zone.
   - Soil properties (texture, clay content, BD, OC content - no highly depleted OC soils)
   - Landscape position and land cover: arable land and grassland basing on CLC
b) Positive SOC sequestration potential (i.e. value in stocks referring to a specific duration, preferably LTEs). Negative potential has been inserted also to enable understanding of the negative effect of a specific practice (e.g. drainage of peatlands).

The mitigation options, showing high potential estimates of SOC sequestration or/and preservation, have been later assessed on their relationship with:

c) Datasets availability at pan-European scale
   - Soil data derived from the European Soil Database-ESDB, available at the European Soil Data Centre (ESDAC). The properties considered for the top-soil layer (0–30 cm) included soil texture, BD, pH, drainage class and rock content at 1 km × 1 km grid resolution.

- Land use and land management practices: CLC (http://www.eea.europa.eu/data-and-maps/data/corine-land-cover), EUROSTAT (http://epp.eurostat.ec.europa.eu) and the AFOLU Data Centre (http://afoludata.jrc.ec.europa.eu).
- Climatic datasets for the period 1901-2000 and projected for 2001–2100 were provided by the Tyndall Centre... The TYN SC 1.0 dataset covers the whole of Europe with a grid of 10’× 10’.

d) Modelling feasibility with CENTURY, specifically:

- High mechanistic representation of the technique
- Management factor can be represented

Only if all these criteria are fulfilled, then the mitigation option could be selected to be simulated.

Some practices are missing or labelled with n\d, because no data on SOC sequestration at European level has been found. Often the studies were lacking in information regarding location/duration or specific management.

For the meta-analysis experimental rates of carbon sequestration in cropland and grassland were derived from LTEs studies exclusively within the EU area simulated. This is a very explorative exercise as experimental management practices are highly site specific and treatments may vary significantly compared to the simulation of specific AMP at pan-European level.

Results and Discussion

From the research carried out a database of metadata has been created. The information derived -where possible are: SOC sequestration rate, reference, location/soil type/climate/LTE duration/management.

The database is divided into the following sub-headings: Grassland management (GM); Crop management (CM); soil amendments; high technologies; water management; land restoration.

Table 3.1 Potential of mitigation options in terms of SOC sequestration (t ha^{-1} yr^{-1}).

Option	SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
LAND USE CONVERSION (arable to grassland; grassland to arable, forest to arable, arable to forest) maintaining permanent grassland	0.3- 0.8	IPCC (2000)	Temperate dry, marginal land	50-yr	Arable to grassland
	0.5	Arrouays (2002)	FRA	n/d	Arable to permanent grassland
	0.35	Conant, Paustian et al. (2001)	Temperate grasslands, rain forests, ambient	Meta-analysis on 115 global studies	Native LC to pasture
	1.01				Cultivation to pasture
	negative	(Soussana, Loiseau et al. 2004); Kätterer, Andersson et al. (2008)	SW, Uppsala, Kungsangen, mean annual temperature 5.1C, precipitation 542mm, gleyic cambisol	Conversion 1850-1920	Grassland to arable land
	0.4			Re-conversion 1971	Arable to grassland
	0.332	Post and Kwon (2000)	US, cool temperate grassland, Ambient	n/d	Recently established permanent grasslands
	0.51	Powlson, Whitmore et al. (2011)	n/d	LTE 35yr	Arable sown to permanent grass
	18 ±11 $MgCha^{-1}$	Poeplau and Don (2012)	Europe SC, D, S, LT	24 LTE study sites	Arable to grassland
	-19 ±7 $MgCha^{-1}$		Europe, I,D,S,CH,		Grassland to arable land
	21 ±13 $MgCha^{-1}$		Europe, S, D, I, DK, NL, LT		Arable land to forest
	-10 ±7 $MgCha^{-1}$		Europe D, IR, SC, CH, A I		Grassland to forest
	1.99	Poeplau, Don et al. (2011)	Mean annual temperature of a test site had to be above 0 and below 18 1C according to the IPCC definition	95 studies In 30 years [modelled]	Arable to grassland
	-1.805				Grassland to arable land
	-1.57				Forest to arable land
	1.12 – 0.8* forest floor included or not				Arable land to forest

Option		SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
		-0.2 - -0.215		of temperate climate		Grassland to forest
GRASSLAND MANAGEMENT	Improved grass production	3	Lal R, Henderlong P et al. (1998)	n/d	6 yr period	Using forage grasses: tall fescue (*Festuca arundinacea*) and smooth bromegrass (*Bromus inermis*)
		0.30	Conant, Paustian et al. (2001)	Temperate grasslands, Ambient	Meta-analysis on 115 global studies	Fertilization (superphosphate, N and manure)
		2.35				Introduction of earthworms
		0.75				Sowing legumes
		0.11				Irrigation
		3.04				Sowing of improved grass species (over seeding, endophyte-infected, endophyte-free fescue)
		0 to 8	Jones and Donnelly (2004)	Temperate grassland	Meta-analysis	Improved grazing (NT)
		1.1	Jones and Donnelly (2004)	relatively productive area, US, Central Plains	50 yr period	Improved grazing
		0.03		US, Colorado arid shortgrass steppe		
		0.3	(Arrouays 2002); Soussana, Loiseau et al. (2004) (Arrouays 2002); Freibauer, Rounsevell et al. (2004)	FRA, managed nutrient poor ley grasslands, ambient	[modelled]	Reduction in N-fertilizer inputs in intensive leys grasslands
		−0.9 - –1.1				Intensification of nutrient-poor grassland
		−0.2				Conversion : permanent grassland to medium-duration leys

Option		SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
		0.2–0.5				Increasing leys duration
		0.3–0.4				Conversion : short duration leys to permanent grassland
		0.2-0.4	Lal (2008) Schuman, Janzen et al. (2002)	humid temperate	n/d	n/d
		0.1-0.2		dry temperate		
		0.1-0.3	Schuman, Janzen et al. (2002)	US rangelands, Ambient	n/d	Poorly or well managed grassland
		0.068 0.19 0.14 0.34	White EM, Krueger CR et al. (1976)	US, South Dakota	n/d	From cultivated to improved pasture for different species: Russian wildrye; crested wheatgrass ; B-I-ALF(full); B-I-ALF(short).
	Managing grazing and cutting (de-intensification)	0.08 -0.09 0.05-0.15	(Thornley, Fowler et al. 1991; Thornley and Cannell 1997)	UK temperate grasslands	Hurley pasture model [modelled]	N inputs of 20 $KgNha^{-1}yr^{-1}$ (upland) and 50 $KgNha^{-1}yr^{-1}$ (lowland) Continuous grazing of 5 and 10 sheep ha^{-1}
		< 0.8	(Niklaus, Wohlfender et al. 2001); Jones and Donnelly (2004)	CH semi-natural calcareous grassland	n/d	Cutting events: 2cuts yr^{-1}, low nutrient
		4.6±2.2 1.9	(Van Kessel, Horwath et al. 2000) Jones and Donnelly (2004)	CH	n/d	Swiss Sown *Trifolium repens* or *Lolium perenne* Cutting events: 4cuts yr^{-1}
		6.3±3.6	(Nitschelm, Lüscher et al. 1997); Jones and Donnelly (2004)	CH	n/d	Swiss Sown *Trifolium repens* Cutting events:

Option		SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
						4cuts yr^{-1}
		2.29	Schapendonk, Dijkstra et al. (1997) Jones and Donnelly (2004)	NL grassland	n/d	sown *Lolium perenne* Cutting events: 10 cuts yr^{-1}
		3.90				high N-input of 800$kg\ ha^{-1}yr^{-1}$
		0.6 - 1.4	(Loiseau and Soussana 1999) Jones and Donnelly (2004)	FRA grasslands	n/d	sown *Lolium perenne* Cutting events: 5 cuts yr^{-1} with low N-input of 160$kg\ ha^{-1}yr^{-1}$
		0.8-1.9				with high N-input of 530$kgCha^{-1}yr^{-1}$
		0.1-0.5	(Arrouays 2002; Freibauer, Rounsevell et al. 2004)	FRA grasslands	n/d	Increase the duration of grass leys
		0.3-0.4				Change from the short duration to permanent grasslands
		1.2±0.5	(Fitter, Graves et al. 1997; Jones and Donnelly 2004)	UK grasslands	n/d	species-rich on limestone soil in solardome Cutting events: 4-5 cuts yr^{-1}
		6.4±0.6				species-poor community on peaty gley solardome without cutting/grazing
		0.6	Schuman, Janzen et al. (2002)	US cultivated lands	n/d	reseeded to grass
		0.33 (max 1.1, min 0.031)	(Gebhart, Johnson et al. 1994; Burke, Lauenroth et al. 1995); Post and Kwon (2000)	US row crops, cool temperate steppe	Meta-analysis	Early aggrading stage of permanent managed grassland

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
			1.78	Teixeira, Domingos et al. (2011)	PT, eight farms, average temperature 15.5–16.8 ◦C, precipitation 200–750mm	2001-2005 [modelled]	Sown bio-diverse permanent pastures rich in legumes
			39.21 $10^6 \, Mg C \, yr^{-1}$ EU15	(Smith, Powlson et al. 1997)	Europe (EU15), grasslands, ambient	[modelled]	Conversion from all arable land to 1:3 yr ley-arable rotation
			Marañón-Jiménez *et al.* (2011)	(Marañón-Jiménez, Castro et al. 2011)	ES, Natural Park, recently burned pine forest. Different treatments including irrigation experiment	Post-fire burnt wood management have effect on SOC But no available data on SOC rate	
CROPLAND MANAGEMENT	Crop variety and species management	N-fixing crops	See legumes in crop rotations session and green manure session				
		Plant breeding	n/d				
		Perennial and permanent crops	0.6	(Smith, Powlson et al. 2000; Freibauer, Rounsevell et al. 2004)	Europe	Estimated from papers	n/d
			0.4	(Arrouays 2002)	FRA	n/d	Sowing grass under perennial crops between rows of vines or fruit trees
		Bioenergy crops	a) 10.12–10.23 $Mg \; C \; ha^{-1}$ b) 6.625 $Mg \; C \; ha^{-1}$	(Hansen, Christensen et al. 2004); EC (2012)	DK	Isotopic ratios experiment	*Miscanthus* plantations (0-100 cm) a) 9yr b) 16yr
			-0.54 - -0.8 $Mg \; C \; ha^{-1}$ loss	(Kochsiek and Knops 2012)	Australia, East-central Nebraska	n/d	Continuous maize with residue production and complete removal

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
	Crop rotations	Rotation type, species selection and other management practices	39.21 $10^6 MgC yr^{-1}$ EU15	Smith, Powlson et al. (1997)	Europe (EU15) European arable lands, ambient	[modelled]	Conversion from all arable land to 1:3 yr ley-arable rotation
			1.5	Buyanovsky and Wagner (1998)	US, Sanborn Field	LTEs	3-yr rotation corn/wheat/clover
			1956-1984 loss 1984-2001 gain 58-77 $MgCha^{-1}$ 1992-2001	Kätterer, Andrén et al. (2004)	SW, Kungsor, Ukno farm, mean annual temperature and precipitation are 5–6 °C and 600–700 mm	1956/1984/2001	From crop rotation dominated by perennial grass leys and spring cereals with manure addition to wheat/barley/rapeseed
			0.4	(Nardi, Morari et al. 2004; Morari, Lugato et al. 2006; Lugato, Paustian et al. 2007)	ITA, PADOVA, Legnaro, sub-humid , annual rainfall 850 mm/yr, fluvi-calcaric cambisol	LTE, since 1962 (Period 1963-2000)	Permanent grass establishment vs. improved long crop rotations + reduced tillage + 20tha^{-1} FYM
			0.02	(Nardi, Morari et al. 2004; Morari, Lugato et al. 2006; Lugato, Paustian et al. 2007)	ITA, PADOVA, Legnaro, sub-humid , annual rainfall 850 mm/yr, fluvi-calcaric cambisol	LTE, since 1962 (Period 1963-2000)	Improved complex Long 6-yr rotation (Maize, Sugar beet, Maize, Wheat, and two yr of LEY CROPPING Alfalfa) +reduced tillage +

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
							20$t\,ha^{-1}$ FYM vs. maize monoculture
			0.6	(Smith, Powlson et al. 2000; Freibauer, Rounsevell et al. 2004)	Europe	Estimated from papers	Deep rooting crops
			0.34-0.42	Persson, Bergkvist et al. (2008)	Southern SW, three sites: Saby, Lanna, Stenstugu	31yr (started in 1965,1968,1969)	2-yr perennial grass and mixed grass/legume leys in a 6-yr crop rotation (oilseed/winter wheat/spring oats/spring barley undersown ley/red clover/grass ley) Different N fertilisation regimes (60-180 $kg\,ha^{-1}$
			0.30-0.44				2-yr perennial grass and mixed grass/legume leys in a 6-yr crop rotation (oilseed/winter wheat/spring oats/spring barley undersown ley/2yr grass ley) Different N fertilisation regimes (60-180 $kg\,ha^{-1}$

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
			0.16-0.22				2-yr perennial grass and mixed grass/legume leys in a 6-yr crop rotation (oilseed/winter wheat/spring oats/spring barley /spring wheat/black fallow Different N fertilisation regimes (60-180 $kg\,ha^{-1}$
			0.357	(West and Post 2002; Holeplass, Singh et al. 2004; Singh and Lal 2005)	Norway, As, Mean annual temperature of the region 5 °C, monthly mean temperature during the growing season 11 °C, mean annual precipitation 785 mm (60% of which is received during the fall and winter), loam soil classified as a Fluvaquentic Humaquept	LTE 37yrs Since 1953	4 crop rotations in combination with mineral fertilizer and animal manure: 4 yr ley in a 6-yr crop rotation
			0.15±0.11	(West and Post 2002) (Powlson, Smith et al. 1998)	n/d	LTEs 67	Enhancing rotation complexity
			0.20 ±0.12*				Enhancing rotation complexity (continuous rotation cropping, *excluding a change From continuous corn (Zeamays L.) to corn-soybean (Glycine max

Option	SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
					L.)
Fallow	*1.07 $gkg^{-1}yr^{-1}$	Fullen, Booth et al. (2006)	Sandy soils in east Shropshire, UK.	LTE, 1991-2001	rye grass ley set-aside
	-0.6 ± 0.2	(Arrouays 2002)	FRA		set aside
	< 0.4	(Smith, Powlson et al. 2000; Freibauer, Rounsevell et al. 2004)	Europe	Estimated from papers	Set-aside of <10% of arable land
	0.82 ±0.07* loss 0.93 ±0.05* loss	Ogle, Breidt et al. (2005)	Temperate moist climate Temperate dry climate	30 LTE studies *factors estimated over 20 yr	Set-aside vs. native (1 or 100%)
	-15.7 loss* and -14.7 loss*	(Christensen and Johnston 1997; Bruun, Christensen et al. 2003; Barré, Eglin et al. 2010)	DK, Askov, south Jutland Lermarken site , annual average precipitation 862 mm, mean annual temperature 7.7C, coarse sand orthic luvisol	LTE, 29 yr *1956-1985	Bare fallow , two blocks (B3/B4), four replicate plots kept free by vegetation by frequent tillage to 20 cm depth, annual NPK fertilizer
	-16.9 loss*	(Barré, Eglin et al. 2010)	FRA, Grignon , silty loam luvisol	LTE, 48yrs *1959-2007	36-plot experiment, bare fallow x 6times x 6blocks. Plots dug by hand twice yr to 25cm depth, kept free from vegetation by hand weeding and herbicide treatment
	-37.8 loss*	(Barré, Eglin et al. 2010)	Russia, Kursk region, forest steppe climatic zone temperate	LTE, 45yrs *1964-2001	5-yrs rotation and continuous crops in a control and application of 20 $t\ ha^{-1} rotation$ and N200P250K150. Bare fallow plot ploughed 22-25cm $2yr^{-1}$ weed

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
							controlled by periodic cultivation
			-43.1 loss*	Barré, Eglin et al. (2010)	UK, Rothamsted, luvisol	LTE, 49yrs *1959-2008	Plough/cultivation 2-4 times yr^{-1} to 22-20cm depth
			-15.6 loss*	Barré, Eglin et al. (2010)	SW, Ultuna, eutric cambisol	LTE, 35yrs *1956-2007	15treatments in 4blocks, 60 plots
			-42.8 loss*	Barré, Eglin et al. (2010)	FRA, Versailles, luvisol	LTE, 80yrs *1928-2008	Dug by hand twice yr^{-1} to 25cm depth
			0.8	(Shrestha, Lal et al. 2013)	US, central Ohio, alfisol	LTE 10 yr	NT corn (*Zea mays* L.) cultivation experiments with fallow plots
			-0.71 ±0.04* loss 0.82 ±0.04* loss	(Ogle, Breidt et al. 2005)	Temperate moist climate Temperate dry climate	30 LTE studies *factors estimated over 20 years	Long-term cultivation vs. native (considered 1 or 100%)
		Cover Crops	0.2-0.5 0.1-0.2	Lal (2008)	humid temperate dry temperate	n/d	n/d
			0.9	(Shrestha, Lal et al. 2013)	Alfisol of central Ohio, USA	LTE 10 yr	NT corn (Zea mays L.) cultivation with cover crop [mixture of rye (Secale cereal), red fescue (Festuca rubra), and blue grass (Poa pratensis L.)]
		Inter cropping or mixed cropping	0.15	Arrouays (2002)	FRA	n/d	Introduction of green manure into intercropping systems
		Contour strip cropping	n/d				
		Relay cropping	n/d				
		Under sowing	n/d				

Option		SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
	Terracing	1.8 ±0.2 gkg^{-1} Vs. 1.3±0.1gkg^{-1}	Hammad, Børresen et al. (2006))	Eastern Mediterranean region, Calcaric Leptosol. Mean annual precipitation 580 mm (90% occurs from October to April), mean annual temperature is 17.1 8C, altitude 900m	Winter season 200-2012	Two adjacent locations: terraced (soil-conserving stonewalled terrace 50 yr old) vs. non terraced Area cultivated with wheat and barley
Agroforestry	Alley cropping	0.2-0.8	(Thevathasan, Gordon et al. 2000; Poeplau, Don et al. 2011); Stavi and Lal (2013)	Southern Canada, marginal soil, Albic Luvisol	12 yr	Hybrid poplar (Populus deltoides × nigra DN-177) (wheat–soybean–maize rotation) at a stand density of 111 trees ha^{-1}
Agroforestry	Alley cropping	3.5 $TgC\ yr^{-1}$	(Smith, Milne et al. 2000)	UK	Estimation to about 10% of the total arable area in the UK of about 6,700 kha	Willow (Salix spp.) SRC on surplus arable land
Agroforestry	Boundary systems	0.1 $MgC\ yr^{-1}$ /100 linear m of hedgerows/ha	(Arrouays 2002; Walter, Merot et al. 2003; Aertsens, De Nocker et al. 2013)	FRA, temperate climate	7 sites	n/d
Agroforestry	Boundary systems	44.46 $MgC\,ha^{-1}$		FRA, Brittany, western part Bocage, Armorican Massif		hedges growing on earth and stone banks high density hedges (200m/ha) 38% hedge effect
Agroforestry	Boundary systems	10.92 $MgC\,ha^{-1}$		FRA, Brittany, western part Bocage, Armorican Massif		hedges growing on earth and stone banks low density hedges (50m/ha) 13% hedge effect

Option	SOC sequestration ($t\ ha^{-1}\ yr^{-1}$)	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
	0.10-1.32 And 0.25-1.25	(Ruiz-Peinado, Moreno et al. 2013)	Iberian dehesas (Mediterranean water-limited agro-silvo-pastoral systems)	n/d	Two common extensive native shrub species (Cistus ladanifer L. and Retama sphaerocarpa (L.) Boiss.)
Other agro forestry options	0.3-0.6 0.2-0.4	Lal (2008)	humid temperate dry temperate	n/d	n/d
	24-90 $Mg C ha^{-1}$	Smith and Falloon (2005); (Nair, Nair et al. 2009; Shrestha, Lal et al. 2013) (Stavi 2013)	arid and semi-arid lowlands	Reviews of synthesis study	n/d
	10–235 $Mg C ha^{-1}$		humid lowlands		
	0.81-0.93	(Lasch, Kollas et al. 2010)	Eastern Germany	modelled	Short-rotation coppice (SRC) plantations with aspen (Populus tremula L.)
	0.4-0.5	(Rytter 2012)	Sweden	n/d	Willow and poplar plantations in abandoned arable land
	6.5 in the tree itself 1.0 in the soil	(Hamon, Dupraz et al. 2009); Aertsens, De Nocker et al. (2013)	Fra, Vézénobres, Mediterranean climate, sandy loam soil	Review of field experiments (US, Canada, France)	poplars (140 trees/ha) of 13 yr [540 kg C/tree in the trunk and 60 kg C/tree in the root system]
	3 in the trees 0.1–0.5 in the soil.		Restinclières, Montpellier, France		14 yr 80 hybrid walnut trees/ha (Juglans regia nigra)
	2		Canada, temperate climate zones		100 trees/ha on grassland
	1.9 $10^9 Mg C yr^{-1}$	(Poeplau, Don et al. 2011; Stavi and Lal 2013)	temperate biome	n/d	n/d
llag e No tillage (NT)	23 $10^6 Mg C yr^{-1}$	Mandlebaum and Nriagu (2011)	EU15	17 European tillage experiments	100% of land converted from conventional to

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
			EU15 0.73±0.39			[modelled]	NT
			1.2 for manure, 1.0 for compost, 0.9 for cover crops and 0.8 for fallow plots	(Shrestha, Lal et al. 2013)	US, Alfisol of central Ohio, USA	LTE 10 yr	NT corn (*Zea mays* L.) cultivation: with (i.e. compost and FYM) cover crop [mixture of rye (*Secale cereal*), red fescue (*Festuca rubra*), and blue grass (*Poa pratensis L.*)].
			0.3-0.4 (±1)	(Smith, Powlson et al. 2000); Freibauer, Rounsevell et al. (2004)	Europe	Estimation from papers	n/d
			0.222 humid 0.097 dry	Six, Ogle et al. (2004)	US, humid (potential evaporation/mean annual precipitation ratio <1) and dry (potential evaporation/mean annual precipitation ratio>1) temperate climates Based on Holdridge Life Zones	Studies review of a dataset	NT vs. conventional tillage Long term adoption >10 yr
			0.175	(Oorts, Bossuyt et al. 2007; Oorts, Merckx et al. 2007)	FRA, Boigneville, Basin of Paris oceanic, long term average temperature 10.8ºC, 650 mm annual precipitation, haplic luvisol	LTE 34yr since 1970-2004	NT plots with maize/wheat rotation (crop residues kept in surface)
			0.429 *In the 0-5cm	(Lopez-Fando and Pardo 2011)	Central ES, semi-arid loamy soil	LTE 17yr 1992-2008	Crop sequence of cheap pea/immaculada barley Comparison of changes from Conventional tillage (mouldboard plow) to NT

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
			0.341 *In the 0-5cm				Crop sequence of cheap pea/immaculada barley Comparison of changes from MT (chisel plow) to NT
			WW 1.05 and WFB 0.75 under NT	(López-Bellido, Fontán et al. 2010)	ES, rainfed Mediterranean Vertisol	LTE 20yr Since 1986	Effect of tillage system, crop rotation, and N fertilization : CT vs. NT; five crop rotations: wheat (Triticum aestivum L.)-chickpea (Cicer arietinum L.) (WC), wheat-sunflower (Helianthus annuus L.) (WS), wheat-bare fallow (WF), wheat-fava-bean (Vicia fava L.) (WFB), and continuous wheat (WW); and N fertilizer applied at four rates (0, 50, 100, and 150 kg N ha -1)
			No significant	(Hermle, Anken et al. 2008)	CH, north-east, orthic Luvisol, mean annual temperature 8.4C, mean precipitation 1183	LTE 19 yr	4 yr crop rotation (winter wheat/maize/winter wheat/winter canola) Mouldboard ploughing, shallow tillage and NT comparisons
			1.16 ±0.02* 1.10 ±0.03*	(Ogle, Breidt et al. 2005)	Temperate moist climate Temperate dry climate	80studies *factors estimated over 20 years	From conventional tillage to NT
			0.2±0.13	(Arrouays 2002)	FRA		NT
			0.57 ±0.14*	(West and Post 2002)	n/d	67 LTEs More than 5yra	From conventional to NT *excluding wheat fallow systems

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr⁻¹)	Management
			0.90 ±0.59				From conventional to NT In a corn-soybean rotation
		Conservation Tillage	0.5-1.0 0.25-0.5	Lal (2008); (Delgado, Groffman et al. 2011; Delgado, Nearing et al. 2013)	humid temperate dry temperate	n/d	n/d
		Conservation Tillage	0.26	Alvarez (2005)	worldwide	Review from field experiments Mean rate	From conventional to CT
		Minimum Tillage (MT) Or Reduced Tillage (RT)	0.072 0.25	(Singh and Lal 2005)	Norway, As, Mean annual temperature of the region 5 °C, monthly mean temperature during the growing season 11 °C, mean annual precipitation 785 mm (60% of which is received during the fall and winter), loam soil classified as a Fluvaquentic Humaquept	LTE	Shallow ploughing (12 cm depth) compared to deep tillage RT + N fertilization (3.5 times more)
			< 0.4	(Smith, Powlson et al. 2000; Freibauer, Rounsevell et al. 2004)	Europe	Estimation from papers	n/d
			0.10 conventional 0.21 RT 0.19 NT	(Metay, Mary et al. 2009; Aertsens, De Nocker et al. 2013)	Fra, Basin of Paris, Boigneville, oceanic, long term average temperature 10.8ºC, 650 mm annual precipitation	LTE 28yr	Corn-wheat rotation CvT vs. RT vs. NT
			0.369	Singh and Lal (2005)	clay soil	n/d	ploughing at 25 cm depth compared with rotovation (10 cm depth)

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
		Compaction	n/d				
		Contour ploughing	n/d				
		Ridging	n/d				
Conservation agriculture (CA)			0.04-1.2	(SoCo 2009)	n/d	n/d	n/d
			0.6-1.2$PgC\,yr^{-1}$	(Lal 2004; Lal 2010)	Global cropland	n/d	n/d
Organic Farming			0.45±0.21* Mean difference	(Gattinger, Muller et al. 2012)	Temperate zones	Meta-analysis 74 studies	Organic vs. non-organic farming systems
NUTRIENT MANAGEMENT	ORGANIC AMENDMENTS	Compost	0.3-0.36	Lal (2008)	Humid/dry temperate	n/d	n/d
			0.2734	Ortas, Akpinar et al. (2013)	TR, Mediterranean soils	LTE	after wheat harvest (0 to 15 cm depth) of for compost application + mycorrhizae inoculation treatment vs. control
			1.34 ±0.08* 1.38 ±0.06*	(Ogle, Breidt et al. 2005)	Temperate moist climate Temperate dry climate	30 LTE studies *factors estimated over 20 years	Amending with high input rotations with organic residues
			1.0	(Shrestha, Lal et al. 2013)	USA, Central Ohio Alfisol	LTE 10 yr	NT corn (*Zea mays* L.) cultivation with compost
			*1.4-2%	Gobin (2011)	BG, Flemish region	Trials 1995-2006	10-15$t\ ha^{-1}yr^{-1}$ VFG-compost application on crops
		Animal manure	6.34	(Thelen, Fronning et al. 2010)	US East Lansing, mixed soil Aubbeenaubbee-Capac sandy loams (Fine-loamy, mixed, mesic Aeric Ochraqualfs) and	three-yr period beginning in 2002	corn-soybean (*Glycine max L.)* rotation with complete corn-stove removal amended with a range of 14730 $kg\ ha^{-1}$ of

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
					Colwood-Brookston loams (Fine-loamy, mixed mesic Typic Argiaquolls and Typic Haplaquolls).		composted dairy manure
			12.6 $10^6 MgC yr^{-1}$ EU15	(Smith, Powlson et al. 1997)	EU15	[modelled for 100yrs]	EU15 arable soils amended with 10 $t\ ha^{-1}yr^{-1}$
			0.05* For only 50 years	Glendining, Powlson et al. (1996); (Powlson, Whitmore et al. 2011)	UK, Broadbalk Wheat Experiment	29 LTEs 40yr	application of 144$kgN\ ha^{-1}yr^{-1}$
			0.688 Vs. 0.34	(Jenkinson 1990; Smith, Powlson et al. 1997; Powlson, Whitmore et al. 2011)	UK, Broadbalk Wheat Experiment	LTE 144yrs	Continuous wheat with application of 35$t\ ha^{-1}yr^{-1}$animal manure vs. inorganic application
			0.92 Vs 0.26	(Smith, Powlson et al. 1997)	UK, Hoosfield	LTE, 123yrs	Continuous barley animal manure application of 35$t\ ha^{-1}yr^{-1}$ vs. inorganic fertiliser
			2.41 Vs 1.89 Vs 1.40	Smith, Powlson et al. (1997)	UK, Woburn Market Garden	LTE, 30yrs	Various vegetable crops with animal manure application of 50 and 25$t\ ha^{-1}yr^{-1}$vs. inorganic fertiliser
			0.58	(Nardi, Morari et al. 2004; Morari, Lugato et al. 2006; Lugato, Paustian et al. 2007)	ITA, PADOVA, Legnaro, sub-humid , annual rainfall 850 mm/yr, fluvi-calcaric cambisol	LTE, since 1962 (Period 1963-2000)	FYM Vs. inorganic fertilizers
			0.96 Vs 0.89 Vs 0.79	(Smith, Powlson et al. 1997; Smith, Smith et al. 1997))	Germany, Bad Lauchstadt, mean precipitation 483mm, mean temperature 8.7C	LTE, 90yrs	Crop rotation (sugar bedspring barley/potatoes/winter wheat). FYM application of 30 and

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
							20 $t\ ha^{-1}$every 2nd yr Vs. inorganic
			1.64 Vs 1.46	(Smith, Powlson et al. 1997; Smith, Smith et al. 1997)	Czech Republic, Praha-Ruzyne in 5 sites annual average precipitation 464mm, annual average temperature 8C	LTE, since 1955, 38 yrs	Classical crop rotation 9yrs, cereal crop rotation 9yrs and crop rotation without legumes 2yrs (sugar beet/spring wheat). Animal manure application of 21$t\ ha^{-1}yr^{-1}$ vs. inorganic
			0.572 vs. 0.522	(Powlson D. S., Smith P. et al. 1996; Christensen and Johnston 1997; Smith, Powlson et al. 1997; Bruun, Christensen et al. 2003)	Denmark, Askov, south Jutland Lermarken and Sandmarken sites, , annual average precipitation 862 mm, mean annual temperature 7.7C, two sites coarse sand Inceptisol and sandy loam Alfisol	LTE, since 1894 100 yrs	4course crop rotation of winter cereals/root crops/spring cereal/clover-grass mixture, animal manure application of 13.5 and 9 $t\ ha^{-1}yr^{-1}$ vs. mineral fertilizer (NPK)
			0.43 Vs 0.36	Smith, Powlson et al. (1997)	FRA, Dehrain	LTE, 112yrs	Crop rotation wheat/sugar beet, animal manure application of 10 $t\ ha^{-1}yr^{-1}$ vs. mineral fertilizer
			2.41 Vs 1.70	Smith, Powlson et al. (1997)	SW, Ultana	LTE, 31yrs	Arable only rotation Animal manure application of 9.54 $t\ ha^{-1}$every 2nd yr vs. mineral fertilizer
			1.46 Vs 1.07	Smith, Powlson et al. (1997)	UK, Woburn Stackyard	LTE, 49yrs (1877-1926)	Continuous crop rotation wheat/barley, animal manure application of

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
							17.6 $t\ ha^{-1}yr^{-1}$ vs. mineral fertilizer
			0.52 Vs 0.39	Smith, Powlson et al. (1997)	PL, Skiemiewice	LTE, 70yrs	Continuous crop rotation of wheat/barley, animal manure application of 30 $t\ ha^{-1}yr^{-1}$ vs. mineral fertilizer both with calcium
			0.67 Vs 0.48				Continuous crop rotation of Wheat and barley Animal manure application of 30 $t\ ha^{-1}yr^{-1}$ vs. mineral fertilizer, both with calcium
			1.152 Vs 0.968	Smith, Powlson et al. (1997)	GE, Thyrow Nutrient Schnieder Deficiency	LTE 25 yrs	4 course crop rotation of maize/barley/potatoes/ barley. Animal manure application of 30$t\ ha^{-1}$every 2nd yr vs. mineral fertilizer
			0.87 Vs 0.654	Smith, Powlson et al. (1997)	GE, Halle	LTE 75 yrs	Continuous rye until 1961, after arable rotation Animal manure application of 12$t\ ha^{-1}yr$ vs. mineral fertilizer
			0.81 Vs 0.74	Smith, Powlson et al. (1997)	GE, Weihenstephan,	LTE 47 yrs	3course arable rotation Animal manure application of 30$t\ ha^{-1}$every 3rd yr vs. mineral fertilizer
			1.2	(Shrestha, Lal et al. 2013)	Alfisol of central Ohio, USA	LTE 10 yrs	NT corn (*Zea mays* L.) cultivation with FYM
			0.042	(Mäder, Fließbach et al. 2002; Fließbach, Oberholzer et al. 2007; Niggli, Fließbach et al. 2009)	CH, Central Europe, Basel, DOK experiment,	LTE since 1977 21yr	Wheat grown in a ley (grass/clover) rotation Organic treatment with

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
					Research Institute FiBL Land Federal Research Institute Agroscope, Haplic Luvisol, mean precipitation averages 785mm and the mean annual temperature is 9.5C.		composted FYM application
			-0.123				Integrated systems with fresh FYM
			-0.084				Integrated Production with fresh FYM and treatment with mineral fertiliser
			-0.207				Integrated Production with mineral fertiliser
			2 Vs. 0	(Berner, Hildermann et al. 2008; Niggli, Fließbach et al. 2009)	CH, Frick reduced tillage trial, Research Institute FiBl, Stagnic Eutric Cambisol, average annual precipitation 1000m, mean annual temperature 8.9C	LTE since 2002	Conventional vs. RT (chisel plough followed by rotary harrow) with application of composted FYM and slurry
			0.37 Vs. -0.25	(Küstermann, Kainz et al. 2008; Niggli, Fließbach et al. 2009)	GE, Scheyern, Experimental Farm, University of Munich,	LTE since 1990	Legume based crop rotation Organic farm vs. conventional
			0.71-0.98	(Kristiansen, Hansen et al. 2005; Thomsen and Christensen 2010)	DK, South Jutland	LTE, 29yrs	Arable soils continuously cropped to silage maize and amended with additional annual input of 8 $Mgha^{-1}$ of manure respectively
			1.2 for manure, 1.0 for compost, 0.9 for cover crops and 0.8 for fallow plots	(Shrestha, Lal et al. 2013)	Alfisol of central Ohio, USA	LTE 10 yr	NT corn (*Zea mays* L.) cultivation: with (i.e. compost and FYM) Cover crop [mixture of rye (*Secale cereal*), red fescue (*Festuca rubra*), and blue grass (*Poa pratensis L.*)].

Option				SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
				6.8 $10^6 MgC yr^{-1}$ EU?	(Smith, Powlson et al. 2000; Smith, Powlson et al. 2000; Smith, Goulding et al. 2001)	EU?		If all manure produced in Europe each yr would be incorporated into arable land in the EU
				7.2	Thelen, Fronning et al. (2010)	US, East Lansing, mixed soil Aubbeenaubbee-Capac sandy loams (Fine-loamy, mixed, mesic Aeric Ochraqualfs) and Colwood-Brookston loams (Fine-loamy, mixed mesic Typic Argiaquolls and Typic Haplaquolls).	three-yr period beginning in 2002	corn-soybean (*Glycine max L.)* rotation with complete corn-stover removal amended with a range of 9714.3 $kg\ ha^{-1}$of beef cattle feedlot manure
				0.068 – 0.227	(Singh and Lal 2005)	Norwegian		fertilizers and manures only by fertilizer application
				0.27	(Nardi, Morari et al. 2004; Morari, Lugato et al. 2006; Lugato, Paustian et al. 2007)	ITA, PADOVA, Legnaro, sub-humid , annual rainfall 850 mm/yr, fluvi-calcaric cambisol	LTE, since 1962 (Period 1963-2000)	slurry vs inorganic fertilizers
				0.3296	Ortas, Akpinar et al. (2013)	Mediterranean soils of Turkey	LTE	after wheat harvest (0 to 15 cm depth) amended with animal manure
			Biosolids: sewage sludge	8.5 $10^6 MgC yr^{-1}$ EU15	Smith, Powlson et al. (1997)	EU15	[modelled]	if all arable soils (11.17% land) would be amended with 1 $t\ ha^{-1} yr^{-1}$
				0.26	(Smith, Powlson et al. 2000; Smith, Andrén et al. 2005)		[Measured]	Sewage sludge application
			Other organic wastes	*1.4-1.6 times higher than initial C	(Madejón, López et al. 2001; Madejón, Murillo et al. 2009)	ES, south western region,	Trials 1995-2006	3 vinasse composts from sugar beet applied on

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
			content		Guadalquivir, Mediterranean, cambisol		crops (corn and sugar beet)
			0.16 $Pg\ C\ yr^{-1}$	(Lehmann and Rondon. 2006; Verheijen 2009; Jeffery, Verheijen et al. 2011; Lehmann, Rillig et al. 2011)	n/d	estimation	From forest residues, mill residues, field crop residues, or urban wastes Considered as biochar production
		Crop residues	14 $10^{6}\ MgC\ yr^{-1}$ EU15	Smith, Powlson et al. (1997)	EU15	[modelled]	EU15 cereal land with 5.07 $t\ ha^{-1}yr^{-1}$ straw incorporation
			0.25-0.49	(Kristiansen, Hansen et al. 2005; Thomsen and Christensen 2010)	DK, South Jutland, 7.8 °C mean annual temperature, 860 mm mean annual precipitation, albeluvisol and humic podzol	4 LTEs (1974-2004)	Arable soils continuously cropped to silage maize and maize roots and straw incorporation
			0.55 calcareous soils, 1.135 gypseous soils 1.450 saline soils	(Badía, Martí et al. 2013)	ES, north-east, Central Ebro, xeric torriorthent soils, 2 calcareous, 2 saline-calcareous, 2 gypseous, Mediterranean climate The annual rainfall was 496 mm in the first year and 286 mm in the second year	6 experimental sites	Barley monoculture agro-ecosystems with straw residue incorporation
			44 $Mg\ C\ ha^{-1}$ 51 $Mg\ C\ ha^{-1}$ 59 $Mg\ C\ ha^{-1}$ = 1.18 sequestration *in 2010	(Buysse, Roisin et al. 2013; Buysse, Schnepf-Kiss et al. 2013)	BG, Hesbaye region, Eutric Cambisol	LTE since 1959 (50 yr)	Residue export FYM Residue restitution after arvest

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
			0.10	(Nardi, Morari et al. 2004; Morari, Lugato et al. 2006; Lugato, Paustian et al. 2007)	ITA, PADOVA, Legnaro, sub-humid , annual rainfall 850 mm/yr, fluvi-calcaric cambisol	LTE, since 1962 (Period 1963-2000)	residue incorporation vs. residue removal
			0.1093	Singh and Lal (2005)	Norway. Southeastern area, Mean annual temperature of the region 5 °C, monthly mean temperature during the growing season 11 °C, mean annual precipitation 785 mm (60% of which is received during the fall and winter), loam soil classified as a Fluvaquentic HumaqueptAs	2 LTEs	2-5 $Mt\ ha^{-1}yr^{-1}$ of straw ploughed every autumn
			0.15	(Arrouays 2002)	FRA	n/d	7 t of cereal straw incorporated
	Inorganic amendments	Synthetic fertilisers	0.6 –1	Strassburg, Kelly et al. (2010)	IS, permanent grasslands on a drained andic gleysol	LTE 43 yr	Fertilizers (ammonium nitrate, ammonium sulphate and calcium nitrate) annually applied. C/N ratio of 12-15
			0.038 0.20	(Nardi, Morari et al. 2004; Morari, Lugato et al. 2006; Lugato, Paustian et al. 2007)	ITA, PADOVA, Legnaro, sub-humid , annual rainfall 850 mm/yr, fluvi-calcaric cambisol	LTE, since 1962 (Period 1963-2000)	high vs low rates of inorganic fertilizers in a wheat monoculture

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
			a- 0.077 b- 0.167 c- 0.040-0.162	Holeplass, Singh et al. (2004).	Norway, As, mean annual temperature 5 °C, monthly mean temperature during the growing season 11 °C, mean annual precipitation 785 mm (60% of which is received during the fall and winter), loam soil Fluvaquentic Humaquept	LTE in 1953	3 6-course rotations: a)continuous spring grain, b) 3 yr spring grain followed by 3 yr root crops, c) 2 yr spring grain followed by 4 yr meadow amended with basal rate of PK fertilizer plus: a- 30-40$kgNha^{-1}$ b- 80-120$kgNha^{-1}$ c- 80-120$kgNha^{-1}$ + 60$Mgha^{-1}$ FYM
			0.068-0.084	Singh and Lal (2005)	Norway, As, mean annual temperature of the region 5 °C, monthly mean temperature during the growing season 11 °C, mean annual precipitation 785 mm (60% of which is received during the fall and winter), loam soil classified as a Fluvaquentic Humaquept	n/d	Fertilizers application

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
		Liming of very acid soils	2-20 times greater in limed than in unlimed soils Long-term effects of liming on soil organic carbon (C org) sequestration are still largely unknown	(Fornara, Steinbeiss et al. 2011; Fornara, Steinbeiss et al. 2011)	UK, south-east, Park Grass Experiment at Rothamsted	LTE since 1856 129yr Small amount of liming in 1880s Test stated in 1903	Application of Ca and Mg-rich materials (liming)
		Natural adsorbents (ameliorative)					
		Modified water soluble polymers (structure generate)	SOC stocks increased, especially in the 0-10 cm soil layer 6-8 $Mg\ Cha^{-1}$ And 2-4$Mg\ Cha^{-1}$	(Rodionov, Nii-Annang et al. 2012)	Germany, Lusatia region, open cast mine Welzow South. Annual temperatures in 2006–2008 from 10.5 to 10.9 ◦C, mean annual precipitation in years 2006 to 2008 396.7, 837.1 and 636.2 mm, respectively.	n/d	Open cast lignite mining: effects of two commercial soil additives (CSA), a hydrophilic polymer mixed with volcanic rock flour and bentonite (a-CSA), and digester solids from biogas plants enriched with humic acids and bentonite (b-CSA), after cultivating perennial crops in monoculture and Helianthus annuus L.-Brassica napus L. in crop rotation systems. CSA incorporated into the top 20 cm soil depth using a rotary spader.

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
			Reduction of CO2 emissions and stabilization of OC	(Piccolo, Spaccini et al. 2011)	Mediterranean soils (Italy) , lab	lab	In situ photopolymerization of SOM under biomimetic catalysis. Three different Mediterranean soils added with a synthetic water-soluble iron-porphyrin
		Biochar	2-109.2 $Pg\ C$ for 1.75 billion of degraded land	(Woolf, Amonette et al. 2010; Stavi 2013); Stavi and Lal (2013)	Global scale	n/d	n/d
			5.5-9.5$Pg\ Cyr^{-1}$	Lehmann, Gaunt et al. (2006)	n/d	projections	pyrolysis
IGH TECHNOLOGIES		Mycorrhizal inoculatio n	0.3296 animal manure 0.2734 compost + mycorrhizal inoc	(Ortas, Akpinar et al. 2013)	Turkey, Mediterranean coast	LTE Since 1996	Effect of inorganic and organic fertilizer treatments (control, chemical fertilizer, animal manure, compost, and compost + mycorrhizal inoculation) in wheat crop (Triticum aestivum)

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
		Co-inoculation of bacterial and cyanobacterial strains	Organic carbon significantly increased in all microbe-inoculated treatments: 0.4-0.5 to 1-1.75%	(Prasanna, Joshi et al. 2012)	India, lab experiment	Pot experiment with rice variety Pusa-1460, comprising 51 treatments	Three selected bacterial strains-PR3, PR7 and PR10 and three cyanobacterial strains CR1, CR2 and CR3 for integrated nutrient management of rice crop
WATER MANAGEMENT SYSTEMS		Small-scale irrigation system	10 Net C fixation of the plantation	(Iglesias, Quiñones et al. 2013)	ES, eastern: commercial orchards planted with Clemenules trees grafted onto Carrizo citrange rootstock in Puzol , Moncada and Vinaroz. Minimum temperature 8.2 ◦C , total annual rainfall 400 mm	Trees 2-14yr aged	Model age-stable citrus agro-ecosystems, drip irrigated and no ground cover
			35.2* $Mg\ C\ ha^{-1}$ (min 22.4-max 41.4) [*13 plus than conventional= 3.25 of sequestration rate]	(Boulal and Gómez-Macpherson 2010)	ES, southern, Cordoba, Fuente Palmera irrigation district, mean annual rainfall of 608 mm	4yr 2004 farm under CA	Conservation irrigation system plus under layer seedling .Minimal cultivation, spring cropping systems(maize-cotton rotation), 4yr irrigated permanent bed planting system vs. conventional

Option	SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr⁻¹)	Management
	32.1* $Mg\ C\ ha^{-1}$ [6.4 plus than conventional = 0.30 sequestration rate]	Ordóñez Fernández, González Fernández et al. (2007)	ES, Seville, Tomejil Agricultural Experimental Station, calcareous vertisol , 79 m above sea level, average annual rainfall of 515 mm, temperature mild maxima of above 40◦C	21yr since the agronomic year 1982/1983	permanent long-term experiment no-till rainfed wheat-based system vs. fully-tilled treatment using the same rotation stored
	37* $Mg\ C\ ha^{-1}$ [3.5 plus than conventional=0.318 sequestration rate]	Hernanz, Sánchez-Girón et al. (2009); (Boulal and Gómez-Macpherson 2010)	ES, central, Madrid El Encı´n Experimental Station, located in Alcala´ de Henares, vertic luvisol with loam texture, 610 m above sea level, average annual temperature of 13.1◦C, annual precipitation averages 430 mm	11yr	rainfed wheat–vetch based systems (Vicia sativa L.) rotation, no tillage vs. fully-tilled treatment
	34-47 $Mg\ C\ ha^{-1}$ [4.7 plus than conventional= 0.31-0.26 sequestration rate]	(Álvaro-Fuentes, López et al. 2008)	ES, northern, semiarid agro-ecosystems of the Ebro River valley	15-18yr	no-till rainfed wheat–barley -based system (Hordeum vulgare L.) vs. fully-tilled treatment accumulated
	0.1-0.2 0.25-0.5	Lal (2008)	humid temperate dry temperate	n/d	n/d
DEGR Land restoration	0.5-1.0 0.4-0.6	Lal (2008)	Lal (2008)	n/d	n/d

Option			SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
			0-0.8	Janssens, Freibauer et al. (2005)	Janssens, Freibauer et al. (2005)	Rate estimation	n/d
			0.3-0.6	(Freibauer, Rounsevell et al. 2004)	(Freibauer, Rounsevell et al. 2004)	n/d	Re-vegetation of abandoned arable land
			0.6	(Arnalds, Guđbergsson et al. 2000)	(Arnalds, Guđbergsson et al. 2000)	n/d	n/d
	Land remediation		0.031	(Burke, Lauenroth et al. 1995)	US	50 yr period of accumulation rate	From abandoned crop fields
	Land rehabilitation		0.0401	(Titlyanova, Rusch et al. 1988)	n/d	n/d	Rehabilitation of mine tailing to grass-forb meadow
			0.282	(Anderson 1977)	n/d	n/d	Rehabilitation of coal mine spoil to a dry grassland
CONSERVA	TION	**Peatland**	*570ha restored Irish peatlands 216600 ha that store 947 Mt c > 4.384 $Mg\ C\ ha^{-1}$	Gobin (2011) www.raisedbogrestoration.ie www.irishbogrestorationproject.ie	IR, Atlantic region	34 sites, 2002-2007 and 2004-2008	Bogs restoration through felling of conifers and the blocking of drains

Option		SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
		0.23	(Gorham 1991; Nilsson, Sagerfors et al. 2008; Billett, Charman et al. 2010)	Northern Hemisphere (boreal/subartic)	n/d	Accumulation in peat *current consensus
		0.2-0.5	(Clymo, Turunen et al. 1998; Cannell, Milne et al. 1999; Billett, Charman et al. 2010)	UK	n/d	net accumulation rate in undrained peat
		0.13-0.21	(Clymo, Turunen et al. 1998; Turunen, Tahvanainen et al. 2001; Turunen, Tomppo et al. 2002; Byrne K.A., Chojnicki B. et al. 2004)	Global, northern latitudes	Average rate since 10000 yrs. ago	Average accumulation rate in peat
		-2.2- -5.4* releases	(Kasimir-Klemedtsson, Klemedtsson et al. 1997; Freibauer 2003)	Finland, Sweden, The Netherlands	Review of three different systems	Peat oxidation due to cultivation
		0.25 -9 (in 9 yr) -5 (in 16 yr) 2*-5* (including biomass) - 1.3 peat decomposition	(Cannell, Milne et al. 1999; Hargreaves, Milne et al. 2003)	UK, Northern Scotland, undisturbed 0.5 m peat, 85-270 m altitude, 800-1100 mm rainfall	LTEs 26 yr	- Accumulation rate in undisturbed deep peat - Ploughed & drained (2-4 yrs.) -10-26 yr newly drained afforested peatland
		0.27 (2004) 0.20 (2005)	(Nilsson, Sagerfors et al. 2008)	Northern Sweden, boreal minerogenic oligotrophic mire in (64°11′N, 19°33′E)	2 yr (2004-2005)	Accumulation rate in peat

Option		SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
		0.72	(Billett, Charman et al. 2010)	UK, South-East Scotland, Auchencorth Moss, 249-300m altitude, 1155mm precipitation, 10C temperature, low-lying ombrotrophic peat	2yrs period: 1996-1998 and 2006-2008	Accumulation rate in peat
		0.56		UK, North England, Moor House, 3 catchments, 450-893m altitude, 1982mm rainfall, 5.3C temperature	13yrs : 1993-2005	Accumulation rate in peat
		-1.36 loss		UK, North England, Bleaklow Plateau, impacted deep peat, 468-630m altitutde, 1554mm rainfall, 7.1C temperature	Since 2006	Extensive erosion, heavy grazing, wildfire, acifying pollutants Extensive restoration activity: drain blocking and revegetation
		0.351-2.091		UK, England and Scotland: Laxford Bridge, raised mire; Lochnagar, sloping blanket mire; Butterburn Flow, raised mire	Historical rates from studies since the mid-20th century	Accumulation rate in peat
		0.23* season	(Tuittila, Vasander et al. 2004)	Southern Finland Aitoneva, Kihnio, 3.5C long-term annual mean temperature, 700 mm mean annual precipitation, treeless mire ditched in 1938	4-yrs field experiment	restoring mire reintroducing Sphagnum angustifolium vegetation in a restored (rewetted) cutaway peatland

Option		SOC sequestration (t ha^{-1} yr^{-1})	Reference	Location, soil type and climate	LTE duration (yr^{-1})	Management
		0.14-0.72	(Malmer, Svensson et al. 1997)	Southern Swedish ombrotrophic mires	Average rate since 10000 yrs. ago	Average accumulation rate in peat
		0.27			End of the 19th century	
		0.17-0.26	(Clymo, Turunen et al. 1998; Turunen, Tahvanainen et al. 2001; Turunen, Tomppo et al. 2002; Byrne K.A., Chojnicki B. et al. 2004)	Finnish mires (decreasing rate with increasing latitude)	n/d	Average accumulation rate in peat
		0.29 0.19		Southern Finnish mires		Average accumulation rate in Ombrotrophic mires vs. minerotrophic mires
		-0.2 - -2.9	(Cannell, Milne et al. 1999)	Finland & Norway	LTE rates	Rate of C loss from drained peat
		2.2 – 4.6 0.8-3.3	Kamp, Gattinger et al. (2001); Flessa, Ruser et al. (2002) (Freibauer, Rounsevell et al. 2004)	GE constructed restored wetland		New crops from arable from grassland
		1.4	(Freibauer, Rounsevell et al. 2004)	Europe, farmed organic soils	calculated	Avoid deep ploughing
		1.4-4.1				More shallow water table
		*sphagnum regrowth *water table raise 0.1-0.3 Freibauer *et al.* (2004)	Gobin (2011) www.ldf.lv/pub/?doc_id=28164 www.lva.gov.lv/daba/eng/biodiv/purvu_e.htm www.imcg.net/ www.peat.lv/index.php?m0=2&lng=en	Latvia, Natura2000, boreal	4 mires 2004-2008	The 4 peatlands (peath depth between 55.75-4 m and area protected between 6636-427 ha) were damaged by drainage, peat extraction, intense forest management, road construction.

C sequestration rates comparison

Among the management options assessed higher C sequestration was shown by: minimizing the time with bare soil, improving recycling of organic materials and increasing yields through efficient N fertilization. The results suggest that C stocks can increase with 1–2 kg C for each kg of mineral N fertilizer applied. Possibilities to decrease C emissions by reduced/minimum tillage were found to be limited under Nordic conditions. Options for reducing C emissions from drained cultivated organic soils are limited when used as cropland. Extensive yields production leads to lower soil C stocks and requires more land. Increasing photosynthesis at the global scale by intensification of crop production was found to be the most effective mitigation option and is a prerequisite for preventing further areal expansion of agriculture

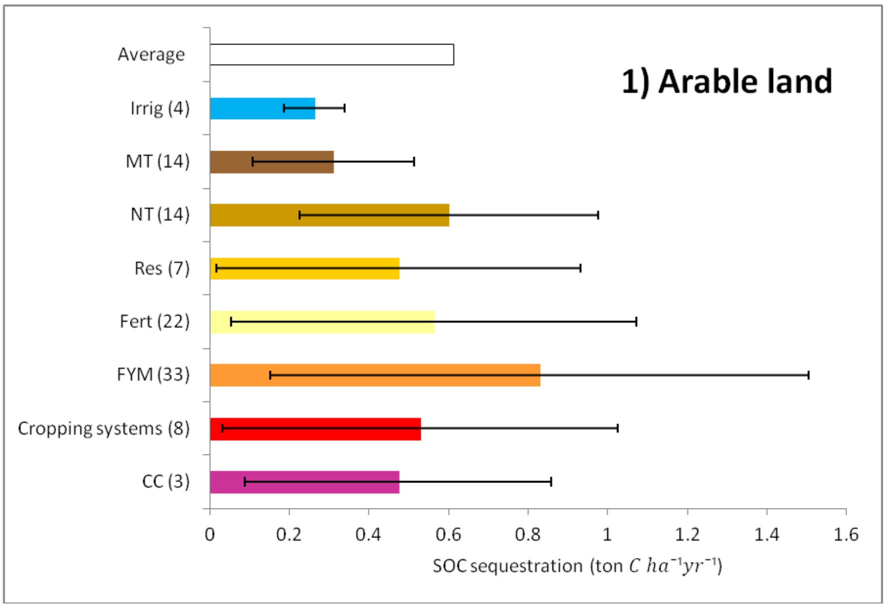
The SOC sequestration data collected in the above table has been further assessed (where possible) for a meta-analysis of selected mitigation measures. The selection was based on availability of information (i.e. rate of sequestration), length of the LTEs (i.e. more than 10 years) and location (i.e. within EU MS). Many studies have been not taken into account because of they were based on short term experiment or were lacking clear comparison or information. Other studies and LTEs took into account a combination of mitigation options: for instance the application of organic amendments (e.g. compost, FYM or crop residues) on a long crop rotation, 3 to 6 years. Conservation Agriculture (CA) is an example of a synergetic system of different management practices: surface working, mulch sowing, direct sowing, no-incorporation of crop residues, crop rotation and vegetation cover (spontaneous vegetation or vegetation resulting from the sowing of appropriate species). In this case the selection based on the mean of comparison.

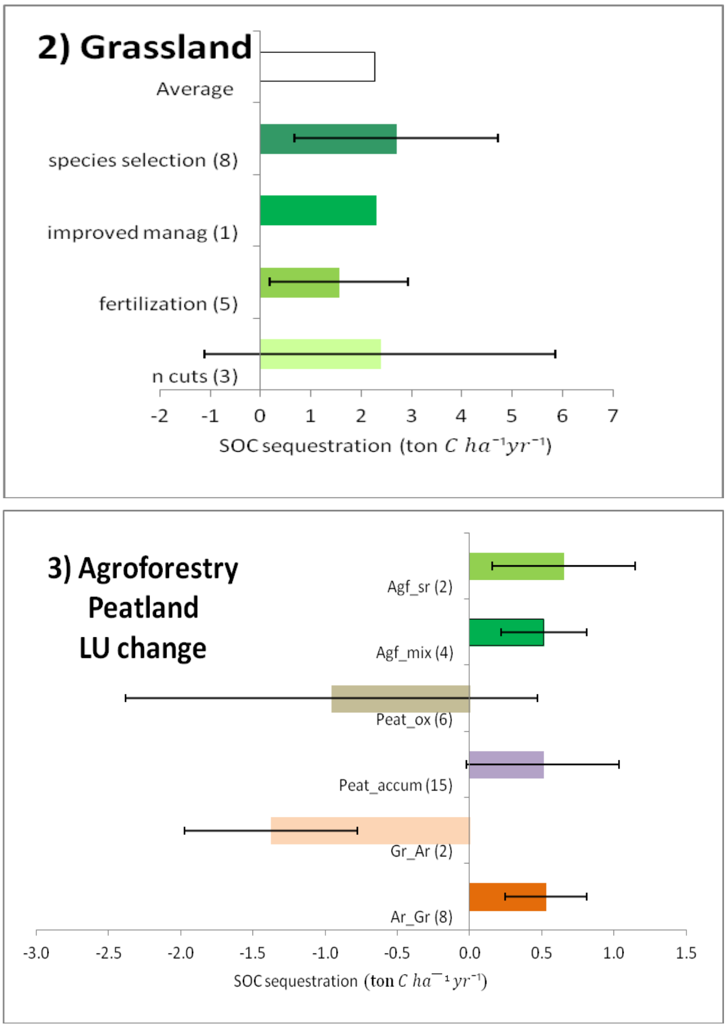
Figure 3.2 visualizes the rate of SOC sequestration for the main practices selected. The practices have been divided into three themes: arable, grassland and others. Every label refers to a different practice. Every bar shows the standard deviation of the values. Arable land related practices showed to range between 0.26 and 0.83 t C ha^{-1} yr^{-1}. Grassland related practices between 1.55 and 2.68 t C ha^{-1} yr^{-1} and the category others has different attitudes in relationship to the practices selected. For example agroforestry mixed and short rotations give positive values around 0.52 and 0.65 respectively t C ha^{-1} yr^{-1}. The oxidation of peatlands and the conversion from grassland to arable give negative values. Peatlands accumulation and conversion from arable land to grassland give very positive ranges. Some options (e.g. minimum tillage) give higher SOC sequestration potential but were not selected for modelling in the next chapter due to a lack of supporting data. All the bars are characterised by a broad variability due to the relative small number of studies and most studies have unique characteristics (i.e. soil type, location, and climate) that give raise to different SOC sequestration rates.

Many practices show local potential but lack either widespread or long-term evidence base. For example following Lal, (2008a) several measures show the influence of the climate on the C sequestration rates in the cool humid temperate regions of Europe the potential rates of C sequestration generally vary from 0.1 – 1.0 t C ha^{-1} yr^{-}1, associated with conservation tillage techniques and erosion control. In the same climatic zones higher rates, 3 – 4 t ha^{-1} yr^{-}1, are associated with set-aside and the restoration of degraded lands, while the restoration of peatlands can give sequestration rates that are an order of magnitude higher. The author says that in drier climates the rates of C sequestration are reduced by around 50%. This climatic dependency has major implications for any EU policy on SOC preservation and sequestration to be produced in the future as there will be major regional variations in the sequestration process. Due to the dependency of the potential of mitigation to the geographical condition of the study there is no single optimum option that, if applied across the EU, could give an absolute certain rate of SOC sequestration. For this reason is necessary to categorized and choose a statistical approach in the selection and assessment of the mitigation practices. In general the potential SOC sequestration of the selected promising mitigation options range from between 0.2 to 1 t C ha^{-1} yr^{-1}.

A US study from Delgado *et al.*, (2011) all the estimated values collected have been divided into positive, high and very high sequestration potential respectively. Agroforestry features such as windbreaks for crops and livestock silvopasture with rotational grazing and riparian forest buffer showed high potential. Same potential has been showed for rotational grazing by livestock, improved grazing management, conversion from cropland to grassland/ natural vegetation / perennial crop, biochar application and wetland restoration.

Figure 3.2 SOC sequestration rates for arable, grassland and others.





CC = cover crops; FYM= farmyard manure application; Fert= N fertilization; Res= crop residues management; NT= no tillage; MT= minimum tillage; Irrig= improved irrigational systems; n cuts= number of cutting events; improved manag= improved management in grassland; Ar_Gr= conversion from arable to grassland; Gr_Ar= conversion from grassland to arable; Peat_accum= peatlands accumulation; Peat_ox= peat oxidation; Agf_mix= agroforestry mixed; Agf_sr= agroforestry short rotation; Average= white bar showing the average for grassland and arable land categories. All the labels show a number in brackets that refers to the number of LTE studies assessed as effective to be accounted.

In Freibauer *et al.*, (2004) and other studies some of the practices proposed are actually impractical as for growing perennial crops on set-aside land in Europe because set-aside is concept is obsolete in the EU.

The major recognized way to sequester SOC would be to avoid changes in land use and to covert the land into the previous natural ecosystem. In the past an extreme negative trend in SOC content has been driven by conversion of the land from forests, permanent grasslands or natural vegetation into arable land. As regard to the conversion of arable land to grassland it seems highly unlikely that removal of large areas of productive land from agriculture will be an option in Europe in the future but this practice could be taken into consideration for all the lands not suitable anymore for cropping because of their low soil quality. Another example is the restoration of previously drained peatlands as there are numerous practical and economic limitations. Nevertheless avoiding drainage of peats in the future should be a practice to be taken into account.

An uncertainty is linked to different interpretations on what constitutes C sequestration. Currently, definitions cover: (a) SOM (except litter); (b) SOM plus litter and roots; (c) below-ground C plus then minimum standing stocks of above-ground litter and biomass. For this reason, depending on the interpretation used, it is difficult to define a real sequestration potential of a measure. Currently the most accepted definition comes from Olson, (2010, 2013) SOC sequestration is literally the process of transferring CO_2 from the atmosphere into the soil through unit plants, plant residues and other organic solids, which are stored or retained in the unit as part of the SOM (humus). The sequestrated SOC process should increase the net SOC storage during and at the end of a study to above the previous pre-treatment baseline levels and result in a net reduction in the CO_2 levels in atmosphere. C not directly from atmosphere and from outside the land unit (e.g. a plot, parcel, field, farm, landscape position, wetland or a forest with boundaries) should not be counted as sequestered SOC (e.g. organic fertilisers, manure, plant residues, natural input processes, etc.).

The benefits of a AMP selected and applied may be reached in time after 15 to 60 years, as a maximum capacity for an ecosystem to store C (West & Post, 2002). As regard to the reversibility of the practice, not all the agricultural mitigation options are reversible, so a subsequent change in the land management can reverse the gains in C sequestration over a similar period of time(Powlson *et al.*, 2011a). As conclusions all the land management changing showing a negative impact on SOC levels should be avoided. Some agricultural mitigation options reviewed may have a limited potential now but they are likely have an increased potential in the long-term. Smith *et al.*, (2008b) lists as promising in long term: better use of fertiliser through precision farming, a wider use of slow and controlled release fertilisers and of nitrification inhibitors, and other practices that reduce N application (and thus N_20 emissions). As well with high technologies such as field diagnostics, fertiliser recommendations from expert/decision support systems and fertiliser placement technologies to improve the efficiency of N use.

In addition, possible changes to the climate of Europe in the coming decades may affect GHGs emissions from agriculture and, consequently, the effectiveness of any specific management practices that have been adopted to minimise them. For example an increase of CO_2 concentrations may affect the plant growth rates, the plant litter composition, drought tolerance, and N demands increasing temperatures are likely to have a positive effect on crop production in colder regions due to a longer growing season. In contrast, increasing temperatures could accelerate decomposition of SOM, releasing stored soil C into the atmosphere (Smith, 2004b). Furthermore, changes in precipitation patterns could change the adaptability of crops or cropping systems selected to reduce GHG emissions. These processes due to climate have high levels of uncertainty; but demonstrate that a practice chosen to sequester C may not have the same effectiveness in the coming decades (Smith *et al.*, 2007c, 2008b).

Agricultural mitigation measures often have synergies with sustainable development policies, and explicitly influences on social, economic, and environmental aspects of sustainability. Many options have co-benefits (e.g. improved efficiency, reduced cost, environmental co-benefits) as well as trade-offs (e.g., increasing other forms of pollution), and balancing these effects will be necessary for a successful implementation.

Seeing the complete long-term picture the adoption of a different practice could be discouraged by different barriers: the limit or the finite capacity of soils to store C; the risk of losing C stored (i.e. because of a change in soil C management); difficulties in establishing a baseline to assess the GHGs net emissions, which is the basis of assessing SOC levels increases, due to the lack of the information needed in some MS; high uncertainty in SOC estimates and lack of information for their assessment; high transaction costs; concerns about competitiveness in agricultural land use; relatively high measurement and monitoring costs; availability of investment capital (e.g. only methodological advances may reduce costs and increase the sensitivity of change detection, as for example improved methods to account soil BD for quantification of changes in SOC stocks); slow progress in technological development and breaking from traditional practices(e.g. new remote sensing techniques, new spectral techniques and modelling) (Powlson *et al.*, 2011a; Stockmann *et al.*, 2013; Jandl *et al.*, 2014). Last but not least an important aspect to be taken into account is the difficulty in changing farmer's habits and compliance (e. g. straw burning is quicker than residue removal and can also control some weeds and diseases). A solution to keep costs low the dominant strategies are those consistent with existing production such as changes in tillage, fertiliser application, livestock diet formulation, and manure management. In the opposite case a land-use change towards a gain in C could displace the existing production (e.g. conversion to grassland or bioenergy crops).

Another aspect to be taken into account if the dislocation of emissions: certain sequestration options adopted could enhance mitigation in a region release, but on the other hand could, in turn, displace the CO_2 emissions in another area, or increasing another GHGs (N_20 and CH_4), reducing the net emission reductions (Powlson *et al.*, 2011a). A practice effective in reducing emissions at one site may be less effective or even counterproductive elsewhere, as example converting natural vegetation into cropland (Powlson *et al.*, 2011a).

The prime consideration is the role of the agricultural sector in providing food for a global population that is expected to continue to grow in the coming decades. As example a growing demand for meat may induce further changes in land use, demand of irrigation and fertilisers. Therefore, one solution would be to expect reasonable SOC sequestration without affecting production rather than absolute SOC sequestration, for example restoring degraded land of limited value for food production. Payments to farmers and land managers for sequestrating C and improving ecosystem services could be a strategy for promoting the adoption of such practices, aimed at mitigating climate change while decreasing environmental footprint of agriculture and sustaining food production.

Synergy between climate change policies, sustainable development and improvement of environmental quality would provide additional incentives to promoting and realising the C sequestration potential of policies and measures in agriculture. And the implementation of C sequestration practices could be seen as opportunities for enhancing a sustainable development and food security.

Conclusions

In the past years there was an impetus for EU policy makers to get rational information on the potential of EU agricultural soils to sequester SOC as climate change mitigation strategy. Nowadays the interested is still high in view of new EU policies legislating sustainable agriculture and food security in a contest of growing population and changing climate. As consequence scientist need to make quantitative founded assessments to identify soil management practices that can sequester and optimize C use. Due to several limitations explained before many studies over-estimated the quantity of possible C sequestration.

The goal of this chapter, and of CAPRESE project, is to review all the scientific literature on experiments on the various mitigation options for their potential impacts on SOC stocks in the agricultural soils of the EU. On the basis of this assessment, a limited number of mitigation options will be selected for simulations in chapter IV. A key factor in this aspect will be to focus on options having a high potential for C sequestration or/and preservation as well as cost-effectiveness and environmental impacts.

Several AMPs appeared to have a significant potential to both preserve and sequester SOC:

- The maintenance of permanent grasslands has showed to have high potential to preserve SOC stocks, while the conversion of arable to grassland has a high sequestration potential from a biochemical potential (no consideration of market conditions).
- Controlled grazing intensity, maintaining a minimum grass coverage, nitrogen-fixing crops, crop rotations including specific species or varieties (cover crops, green manure and catch crops) and adopting longer rotation, terracing, reduced tillage, residue incorporation, contour ploughing, organic amendments (e.g. compost, farmyard manure) and balanced fertilisation appear, given optimum conditions, to give sequestration rates of up to 1 t C ha^{-1} yr^{-1}.

- Intercropping or mixed cropping, contour strip cropping, relay cropping, undersowing, mulching, weed management, stale seedbeds, buffer strips, no tillage, conservation tillage, ridge tillage, alley cropping, silvopasture, boundary systems, wind breaks and liming appears to have a limited or uncertain potential to preserve and increase SOC stocks (no consideration of market conditions). However, these measures are often difficult to quantify due to a lack of supporting information and studies in the EU.
- Increased removal of crop residues may lead to a reduction in SOC stocks unless other organic material is added to compensate. There may also be secondary soil degradation consequences.
- The use of genetically modified crops, biochar, precision farming and irrigation appear to have some potential. However, data are lacking for effective assessments or scenario developments.
- Peatlands should be preserved to retain high SOC pool. Cultivation and drainage of peatlands give raise to major SOC losses.
- Several measures would benefit from being implemented in combination with other practices (e.g. crop residue and low tillage, increased cutting of grasslands with lay-based rotation, cover crops in arable rotation). Conservation agriculture, organic farming and integrated pest management systems lend themselves to such cohesive approaches.

While these practices have been shown to be theoretically effective at C sequestration, many lack robust assessments both geographically and/or over time.

From the information collected it's clear that a soil management practice could have a high potential SOC sequestration if applied within site-specific conditions (soil properties\climate) and land use and if barriers of implementation can be overcome. Sequestration rates and saturation levels vary between measures, but generally accumulation rates tend to be higher in humid conditions.

For this reason there is no single option that, if applied across the EU, would give a uniform rate of soil carbon sequestration, consequently each practice need to be evaluated for individual agricultural systems based on climate, edaphic, social setting, and historical patterns of land use and management. When considering which practices to be implemented at national level there is no common size. Each MS would have to decide on key issues for its preservation, mitigation and sequestration strategy, recognising its national environmental, social and economic circumstances.

Another important aspect to keep in mind is that any practice that sequester or maintain SOC content is likely to have positive impacts on soil properties and functions (Powlson *et al.*, 2011a). Many practices provide secondary benefits ranging from improvements in soil characteristics such as structure, water retention, biodiversity, prevention of erosion and land degradation. Even practices that have no positive role in climate change mitigation could results to be beneficial in other ways showing how SOC sequestration or even maintenance is a key policy aspect.

Acknowledgements

This chapter is largely based on the work done under the CAPRESE project[20].

[20] http://eusoils.jrc.ec.europa.eu/library/Themes/SOC/CAPRESE/ and http://mars.jrc.ec.europa.eu/mars/Projects/CAPRESE

References

Aertsens J., De Nocker L., Gobin A., 2013. "Valuing the carbon sequestration potential for European agriculture" in Land Use Policy 31: 584-594.

Aguilera, E., Lassaletta, L., Gattinger, A., & Gimeno, B. S. (2013). Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. Agriculture, Ecosystems and Environment, 168, 25–36. doi:10.1016/j.agee.2013.02.003

Alluvione, F., Fiorentino, N., Bertora, C., Zavattaro, L., Fagnano, M., Chiarandà, F. Q., & Grignani, C. (2013). Short-term crop and soil response to C-friendly strategies in two contrasting environments. European Journal of Agronomy, 45, 114–123. doi:10.1016/j.eja.2012.09.003

Alvarez R., 2005. "A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage" in Soil Use and Management 21: 38-52.

Anderson D.W., 1977. "Early stages of soil formation on glacial till mine spoils in a semi-arid climate" in Geoderma 19: 11-19.

Arnalds Ó., Gudbergsson G., Gudmundsson J., 2000. "Carbon sequestration and reclamation of severely degraded soils in Iceland. " in Búvísindi 13: 87-97.

Arrouays D., J. Balesdent, J.C. Germon, P.A. Jayet, J.F. Soussana, P. Stengel, 2002. "Increasing carbon stocks in French agricultural soils? An assessment report compiled by the French Institute for Agricultural Research (INRA)" Page, French Institute for Agricultural Research (INRA).

Barré P., Eglin T., Christensen B.T., Ciais P., Houot S., Kätterer T., Van Oort F., Peylin P., Poulton P.R., Romanenkov V., Chenu C., 2010. "Quantifying and isolating stable soil organic carbon using long-term bare fallow experiments" in Biogeosciences 7: 3839-3850.

Berner A., Hildermann I., Fließbach A., Pfiffner L., Niggli U., Mäder P., 2008. "Crop yield and soil fertility response to reduced tillage under organic management" in Soil and Tillage Research 101: 89-96.

Billett M.F., Charman D.J., Clark J.M., Evans C.D., Evans M.G., Ostle N.J., Worrall F., Burden A., Dinsmore K.J., Jones T., Mcnamara N.P., Parry L., Rowson J.G., Rose R., 2010. "Carbon balance of UK peatlands: Current state of knowledge and future research challenges" in Climate Research 45: 13-29.

Boulal H., Gómez-Macpherson H., 2010. "Dynamics of soil organic carbon in an innovative irrigated permanent bed system on sloping land in southern Spain" in Agriculture, Ecosystems and Environment 139: 284-292.

Bruun S., Christensen B.T., Hansen E.M., Magid J., Jensen L.S., 2003. "Calibration and validation of the soil organic matter dynamics of the Daisy model with data from the Askov long-term experiments" in Soil Biology and Biochemistry 35: 67-76.

Burke I.C., Lauenroth W.K., Coffin D.P., 1995. "Soil organic matter recovery in semiarid grasslands: Implications for the conservation reserve program" in Ecological Applications 5: 793-801.

Buyanovsky G.A., Wagner G.H., 1998. "Carbon cycling in cultivated land and its global significance" in Global Change Biology 4: 131-141.

Byrne K.A., Chojnicki B., Christensen T.R., Drösler M., Freibauer A., Friborg T., Frolking S., Lindroth A., Mailhammer J., Malmer N., Selin P., Turunen J., Valentini R., L. Z.,

2004. "EU peatlands: Current carbon stocks and trace gas fluxes. Discussion paper to the project CarboEurope-GHG Concerted Action Synthesis of the European Greenhouse Gas Budget. Report 4/2004." Page, Viterbo, Italy.

Campbell, C. A., Janzen, H. H., Paustian, K., Gregorich, E. G., Sherrod, L., Liang, B. C., & Zentner, R. P. (2005). Carbon storage in soils of the North American Great Plains: Effect of cropping frequency. Agronomy Journal, 97(2), 349–363. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-15944385365&partnerID=40&md5=b722558c2cf9673c342cd6c617d4b596

Cannell M.G.R., Milne R., Hargreaves K.J., Brown T.a.W., Cruickshank M.M., Bradley R.I., Spencer T., Hope D., Billett M.F., Adger W.N., Subak S., 1999. "National inventories of terrestrial carbon sources and sinks: The U.K. Experience" in Climatic Change 42: 505-530.

Christensen B.T., Johnston A.E., 1997. "Chapter 18 Soil organic matter and soil quality-Lessons learned from long-term experiments at Askov and Rothamsted" Page.

Clymo R.S., Turunen J., Tolonen K., 1998. "Carbon accumulation in peatland" in Oikos 81: 368-388.

Conant R.T., Paustian K., Elliott E.T., 2001. "Grassland management and conversion into grassland: Effects on soil carbon" in Ecological Applications 11: 343-355.

Creamer, R. E., Brennan, F., Fenton, O., Healy, M. G., Lalor, S. T. J., Lanigan, G. J., … Griffiths, B. S. (2010). Implications of the proposed Soil Framework Directive on agricultural systems in Atlantic Europe - a review. Soil Use and Management, 26(3), 198–211. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-77956097948&partnerID=40&md5=a9e2c3e9db27a5fc362fc86e841d539a

Davidson, E. a, & Janssens, I. a. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 440(7081), 165–173. doi:10.1038/nature04514

Delgado J.A., Groffman P.M., Nearing M.A., Goddard T., Reicosky D., Lal R., Kitchen N.R., Rice C.W., Towery D., Salon P., 2011. "Conservation practices to mitigate and adapt to climate change" in Journal of Soil and Water Conservation 66: 118A-129A.

Delgado, J. a, Nearing, M. a, & Rice, C. W. (2013). Conservation practices for climate change adaptation. Advances in Agronomy (1st ed., Vol. 121, pp. 47–115). Copyright © 2013 Elsevier Inc. doi:10.1016/B978-0-12-407685-3.00002-5

Delgado, J. a., Groffman, P. M., Nearing, M. a., Goddard, T., Reicosky, D., Lal, R., … Salon, P. (2011). Conservation practices to mitigate and adapt to climate change. Journal of Soil and Water Conservation, 66(4), 118A–129A. doi:10.2489/jswc.66.4.118A

Don, A., Schumacher, J., & Freibauer, A. (2011). Impact of tropical land-use change on soil organic carbon stocks - a meta-analysis. Global Change Biology, 17(4), 1658–1670. doi:10.1111/j.1365-2486.2010.02336.x

EC (2012). COM((2012)46 final. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, The implementation of the Soil Thematic Strategy and on going activities. " Page, Brussels, European Commission.

EC. (2009a). (SEC(2009) 417). Commission staff working document. Accompanying the White Paper, Adapting to climate change: towards a European framework for action. Adapting to climate change: the challenge for European agriculture and rural areas. (E.

Commission, Ed.). Brussels: European Commission. Retrieved from http://ec.europa.eu/agriculture/climate-change/pdf/sec2009_1093_en.pdf

EC. (2009b). Final Report on the project Sustainable Agriculture and Soil Conservation (SoCo) (p. 169). Office for Official Publications of the European Communities, Luxembourg: EC. Retrieved from http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/EUR23820.pdf

FAO (2001). Soil carbon sequestration for improved land management. (R. M., Ed.) (World soil.). Rome: Fao.

Fitter A.H., Graves J.D., Wolfenden J., Self G.K., Brown T.K., Bogie D., Mansfield T.A., 1997. "Root production and turnover and carbon budgets of two contrasting grasslands under ambient and elevated atmospheric carbon dioxide concentrations" in New Phytologist 137: 247-255.

Flessa H., Ruser R., Dörsch P., Kamp T., Jimenez M.A., Munch J.C., Beese F., 2002. "Integrated evaluation of greenhouse gas emissions (CO2, CH4, N2O) from two farming systems in southern Germany" in Agriculture, Ecosystems and Environment 91: 175-189.

Fließbach A., Oberholzer H.R., Gunst L., Mäder P., 2007. "Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming" in Agriculture, Ecosystems and Environment 118: 273-284.

Fornara D.A., Steinbeiss S., Mcnamara N.P., Gleixner G., Oakley S., Poulton P.R., Macdonald A.J., Bardgett R.D., 2011a. "Increases in soil organic carbon sequestration can reduce the global warming potential of long-term liming to permanent grassland" in Global Change Biology 17: 1925-1934.

Freibauer, A., Rounsevell, M. D. a, Smith, P., & Verhagen, J. (2004). Carbon sequestration in the agricultural soils of Europe. Geoderma, 122(1), 1–23. doi:10.1016/j.geoderma.2004.01.021

Freibauer A., 2003. "Regionalised inventory of biogenic greenhouse gas emissions from European agriculture" in European Journal of Agronomy 19: 135-160.

Fullen M.A., Booth C.A., Brandsma R.T., 2006. "Long-term effects of grass ley set-aside on erosion rates and soil organic matter on sandy soils in east Shropshire, UK" in Soil and Tillage Research 89: 122-128.

Gattinger A., Muller A., Haeni M., Skinner C., Fliessbach A., Buchmann N., Mäder P., Stolze M., Smith P., Scialabba N.E.H., Niggli U., 2012. "Enhanced top soil carbon stocks under organic farming" in Proceedings of the National Academy of Sciences of the United States of America 109: 18226-18231.

Gebhart D.L., Johnson H.B., Mayeux H.S., Polley H.W., 1994. "The CRP increases soil organic carbon" in Journal of Soil and Water Conservation 49: 488-492.

Glendining M.J., Powlson D.S., Poulton P.R., Bradbury N.J., Palazzo D., Li X., 1996. "The effects of long-term applications of inorganic nitrogen fertilizer on soil nitrogen in the Broadhalk Wheat Experiment" in Journal of Agricultural Science 127: 347-363.

Gobin P. Campling, L. Janssen, N. Desmet, H. van Delden, J. Hurkens, P. Lavelle and S. Berman, A. (2011). Soil organic matter management across the EU – best practices, constraints and trade-offs. Final Report for the European Commission’s DG Environment. (p. 140). Retrieved from http://www.riks.nl/resources/papers/full_report_som.pdf

Gorham E., 1991. "Northern peatlands: role in the carbon cycle and probable responses to climatic warming" in Ecological Applications 1: 182-195.

Guo, L., & Gifford, R. (2002). Soil carbon stocks and land use change: a meta analysis. Global Change Biology, 345–360. Retrieved from http://onlinelibrary.wiley.com/doi/10.1046/j.1354-1013.2002.00486.x/full

Hammad A.H.A., Børresen T., Haugen L.E., 2006. "Effects of rain characteristics and terracing on runoff and erosion under the Mediterranean" in Soil and Tillage Research 87: 39-47.

Hamon X., Dupraz C., Liagre F., 2009. "L'Agroforesterie: Outil de Séquestration du Carbone en Agriculture" Page.

Hansen E.M., Christensen B.T., Jensen L.S., Kristensen K., 2004. "Carbon sequestration in soil beneath long-term Miscanthus plantations as determined by 13C abundance" in Biomass and Bioenergy 26: 97-105.

Hargreaves K.J., Milne R., Cannell M.G.R., 2003. "Carbon balance of afforested peatland in Scotland" in Forestry 76: 299-317.

Hermle S., Anken T., Leifeld J., Weisskopf P., 2008. "The effect of the tillage system on soil organic carbon content under moist, cold-temperate conditions" in Soil and Tillage Research 98: 94-105.

Holeplass H., Singh B.R., Lal R., 2004. "Carbon sequestration in soil aggregates under different crop rotations and nitrogen fertilization in an inceptisol in southeastern Norway" in Nutrient Cycling in Agroecosystems 70: 167-177.

Hoogmoed, M., Cunningham, S. C., Thomson, J. R., Baker, P. J., Beringer, J., & Cavagnaro, T. R. (2012). Does afforestation of pastures increase sequestration of soil carbon in Mediterranean climates? Agriculture, Ecosystems & Environment, 159, 176–183. doi:10.1016/j.agee.2012.07.011

IPCC. (2007). Climate Change 2007: Synthesis report. Fourth Assessment report of the IPCC, AR4. Cambridge University Press, Cambridge. Retrieved from http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

Iglesias D.J., Quiñones A., Font A., Martínez-Alcántara B., Forner-Giner M.T., Legaz F., Primo-Millo E., 2013. "Carbon balance of citrus plantations in Eastern Spain" in Agriculture, Ecosystems and Environment 171: 103-111.

Ipcc, 2000. "Land Use, Land-Use Change and Forestry" (ed Robert T. Watson I.R.N., Bert Bolin, N. H. Ravindranath, David J. Verardo, David J. Dokken) Page, Cambridge University Press, UK, IPCC.

Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M. F., Bampa, F., van Wesemael, B., … Miglietta, F. (2014). Current status, uncertainty and future needs in soil organic carbon monitoring. Science of the Total Environment, 468-469, 376–383. doi:10.1016/j.scitotenv.2013.08.026

Janssens I.A., Freibauer A., Schlamadinger B., Ceulemans R., Ciais P., Dolman A.J., Heimann M., Nabuurs G.J., Smith P., Valentini R., Schulze E.D., 2005. "The carbon budget of terrestrial ecosystems at country-scale - A European case study" in Biogeosciences 2: 15-26.

Jeffery, S., Verheijen, F. G. a. G. A., van der Velde, M., & Bastos, a. C. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agriculture, Ecosystems & Environment, 144(1), 175–187. doi:10.1016/j.agee.2011.08.015

Jenkinson D.S., 1990. "The turnover of organic carbon and nitrogen in soil" in Philosophical Transactions - Royal Society of London, B 329: 361-368.

Jones M.B., Donnelly A., 2004. "Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO2" in New Phytologist 164: 423-439.
Kamp T., Gattinger A., Wild U., Munch J.C., 2001. "Methane and nitrous oxide emissions from drained and restored peatland in the Danube Valley (Southern Germany)" in Verhandlungen der Gesellschaft fur Okologie 31: 193.
Kasimir-Klemedtsson Å., Klemedtsson L., Berglund K., Martikainen P., Silvola J., Oenema O., 1997. "Greenhouse gas emissions from farmed organic soils: A review" in Soil Use and Management 13: 245-250.
Kimble R. Lal, Follet R., J. (2002). Agricultural Practices and Policies for Carbon Sequestration in Soil . Boca Raton, FL, USA: Lewis Publishers. Retrieved from http://afrsweb.usda.gov/SP2UserFiles/Place/36450000/Products-Reprints/2002/983.pdf
Kochsiek A.E., Knops J.M.H., 2012. "Maize cellulosic biofuels: soil carbon loss can be a hidden cost of residue removal" in GCB Bioenergy 4: 229-233.
Kristiansen S.M., Hansen E.M., Jensen L.S., Christensen B.T., 2005. "Natural 13C abundance and carbon storage in Danish soils under continuous silage maize" in European Journal of Agronomy 22: 107-117.
Kätterer T., Andersson L., Andrén O., Persson J., 2008. "Long-term impact of chronosequential land use change on soil carbon stocks on a Swedish farm" in Nutrient Cycling in Agroecosystems 81: 145-155.
Kätterer T., Andrén O., Persson J., 2004. "The impact of altered management on long-term agricultural soil carbon stocks - A Swedish case study" in Nutrient Cycling in Agroecosystems 70: 179-187.
Kätterer, T., & Kirchmann, H. (n.d.). Carbon sequestration in cropland Management options evaluated in long-term field experiments in northern Europe.
Küstermann B., Kainz M., Hülsbergen K.J., 2008. "Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems" in Renewable Agriculture and Food Systems 23: 38-52.
Lal, R. (2011). SOLAW Background thematic report TR04B Soil Carbon Sequestration. Rome.
Lal R., 2010. "A dual response of Conservation Agriculture to Climate Change: Reducing CO2 Emissions and the carbon sink" in: Proceedings of the European Congress on Conservation Agriculture: Towards agro-environmental climate and energetic sustainability. (ed Edición Del Ministerio De Medio Ambiente Y Medio Rural Y Marino E.C.C.L.a.E.D.a.D.C.S.V.) Page, Madrid, Spain.
Lal, R. (2010). Beyond Copenhagen: Mitigating climate change and achieving food security through soil carbon sequestration. Food Security, 2(2), 169–177. doi:10.1007/s12571-010-0060-9
Lal R., 2004. "Carbon emission from farm operations" in Environment International 30: 981-990.
Lal, R. (2008). Carbon sequestration. Philosophical Transactions of the Royal Society B-Biological Sciences, 363, 815–830.
Lal, R. (2008). Soil carbon stocks under present and future climate with specific reference to European ecoregions. Nutrient Cycling in Agroecosystems, 81(2), 113–127. doi:10.1007/s10705-007-9147-x

Lal, R., Follett, R. F., Stewart, B. A., & Kimble, J. M. (2007). SOIL CARBON SEQUESTRATION TO MITIGATE CLIMATE CHANGE AND ADVANCE FOOD SECURITY.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. Science, 304(5677), 1623–1627. doi:10.1126/science.1097396

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. Geoderma, 123(1-2), 1–22. doi:10.1016/j.geoderma.2004.01.032

Lal R, Henderlong P, M F. (1998) Forages and row cropping effects on soil organic carbon and nitrogen contents. In: Management of carbon sequestration in soil. (ed Raton B.) pp Page. FL, USA, CRC Press.

Lasch P., Kollas C., Rock J., Suckow F., 2010. "Potentials and impacts of short-rotation coppice plantation with aspen in Eastern Germany under conditions of climate change" in Regional Environmental Change 10: 83-94.

Lehmann J., Gaunt J., Rondon M., 2006. "Bio-char sequestration in terrestrial ecosystems - A review" in Mitigation and Adaptation Strategies for Global Change 11: 403-427.

Lehmann J., Rillig M.C., Thies J., Masiello C.A., Hockaday W.C., Crowley D., 2011. "Biochar effects on soil biota - A review" in Soil Biology and Biochemistry 43: 1812-1836.

Lehmann J., Rondon. M., 2006. "BioChar soil management on highly weathered soils in the humid tropics. In: N. Uphoff et al. (eds.), Biological approaches to sustainable soil systems. " in Florida: CRC Press, Taylor and Francis Group. p. 517-530.

Loiseau P., Soussana J.F., 1999. "Elevated [CO2], temperature increase and N supply effects on the accumulation of below-ground carbon in a temperate grassland ecosystem" in Plant and Soil 212: 123-134.

Lopez-Fando C., Pardo M.T., 2011. "Soil carbon storage and stratification under different tillage systems in a semi-arid region" in Soil and Tillage Research 111: 224-230.

Lugato E., Paustian K., Giardini L., 2007. "Modelling soil organic carbon dynamics in two long-term experiments of north-eastern Italy" in Agriculture, Ecosystems and Environment 120: 423-432.

López-Bellido R.J., Fontán J.M., López-Bellido F.J., López-Bellido L., 2010. "Carbon sequestration by tillage, rotation, and nitrogen fertilization in a mediterranean vertisol" in Agronomy Journal 102: 310-318.

Madejón E., López R., Murillo J.M., Cabrera F., 2001. "Agricultural use of three (sugar-beet) vinasse composts: Effect on crops and chemical properties of a Cambisol soil in the Guadalquivir river valley (SW Spain)" in Agriculture, Ecosystems and Environment 84: 55-65.

Madejón E., Murillo J.M., Moreno F., López M.V., Arrue J.L., Alvaro-Fuentes J., Cantero C., 2009. "Effect of long-term conservation tillage on soil biochemical properties in Mediterranean Spanish areas" in Soil and Tillage Research 105: 55-62.

Mäder P., Fließbach A., Dubois D., Gunst L., Fried P., Niggli U., 2002. "Soil fertility and biodiversity in organic farming" in Science 296: 1694-1697.

Malmer N., Svensson G., Wallén B., 1997. "Mass balance and nitrogen accumulation in hummocks on a South Swedish bog during the late Holocene" in Ecography 20: 535-549.

Mandlebaum S., Nriagu J. (2011) Carbon Sequestration and Agriculture. In: Encyclopedia of Environmental Health. (ed Editor-in-Chief: jerome O.N.) pp Page. Burlington, Elsevier.

Marañón-Jiménez S., Castro J., Kowalski A.S., Serrano-Ortiz P., Reverter B.R., Sánchez-Cañete E.P., Zamora R., 2011. "Post-fire soil respiration in relation to burnt wood management in a Mediterranean mountain ecosystem" in Forest Ecology and Management 261: 1436-1447.
McSherry, M. E., & Ritchie, M. E. (2013). Effects of grazing on grassland soil carbon: a global review. Global Change Biology, 19(5), 1347–57. doi:10.1111/gcb.12144
Metay A., Mary B., Arrouays D., Labreuche J., Martin M., Nicolardot B., Germon J.C., 2009. "Effects of reduced or no tillage practices on C sequestration in soils in temperate regions" in Effets des techniques culturales sans labour sur le stockage de carbone dans le sol en contexte climatique tempéré 89: 623-634.
Morari, F., Lugato, E., Berti, a., & Giardini, L. (2006). Long-term effects of recommended management practices on soil carbon changes and sequestration in north-eastern Italy. Soil Use and Management, 22(1), 71–81. doi:10.1111/j.1475-2743.2005.00006.x
Nair P.K.R., Nair V.D., Kumar B.M., Haile S.G., 2009. "Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal" in Environmental Science and Policy 12: 1099-1111.
Nardi S., Morari F., Berti A., Tosoni M., Giardini L., 2004. "Soil organic matter properties after 40 years of different use of organic and mineral fertilisers" in European Journal of Agronomy 21: 357-367.
Niggli U., Fließbach A., Hepperly P., Scialabba N.E.H., 2009. "Low Greenhouse Gas Agriculture: Mitigation and Adaptation Potential of Sustainable Farming Systems" in: Rev. 2. Page, Rome, FAO.
Niklaus P.A., Wohlfender M., Siegwolf R., Körner C., 2001. "Effects of six years atmospheric CO2 enrichment on plant, soil, and soil microbial C of a calcareous grassland" in Plant and Soil 233: 189-202.
Nilsson M., Sagerfors J., Buffam I., Laudon H., Eriksson T., Grelle A., Klemedtsson L., Weslien P., Lindroth A., 2008. "Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire - A significant sink after accounting for all C-fluxes" in Global Change Biology 14: 2317-2332.
Nitschelm J.J., Lüscher A., Hartwig U.A., Van Kessel C., 1997. "Using stable isotopes to determine soil carbon input differences under ambient and elevated atmospheric CO2 conditions" in Global Change Biology 3: 411-416.
Ogle S.M., Breidt F.J., Paustian K., 2005. "Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions" in Biogeochemistry 72: 87-121.
Olson, K. R. (2010). Impacts of tillage, slope, and erosion on soil organic carbon retention. Soil Science, 175(11), 562–567. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-78649367747&partnerID=40&md5=561ae7bb511d9d65722400da62115d1a
Olson, K. R. (2013). Soil organic carbon sequestration, storage, retention and loss in U.S. croplands: Issues paper for protocol development. Geoderma, 195-196, 201–206. doi:10.1016/j.geoderma.2012.12.004
Oorts K., Bossuyt H., Labreuche J., Merckx R., Nicolardot B., 2007a. "Carbon and nitrogen stocks in relation to organic matter fractions, aggregation and pore size distribution in no-tillage and conventional tillage in northern France" in European Journal of Soil Science 58: 248-259.

Oorts K., Merckx R., Gréhan E., Labreuche J., Nicolardot B., 2007b. "Determinants of annual fluxes of CO2 and N2O in long-term no-tillage and conventional tillage systems in northern France" in Soil and Tillage Research 95: 133-148.
Ortas I., Akpinar C., Lal R., 2013. "Long-term impacts of organic and inorganic fertilizers on carbon sequestration in aggregates of an entisol in mediterranean Turkey" in Soil Science 178: 12-23.
Persson T., Bergkvist G., Kätterer T., 2008. "Long-term effects of crop rotations with and without perennial leys on soil carbon stocks and grain yields of winter wheat" in Nutrient Cycling in Agroecosystems 81: 193-202.
Piccolo A., Spaccini R., Nebbioso A., Mazzei P., 2011. "Carbon sequestration in soil by in situ catalyzed photo-oxidative polymerization of soil organic matter" in Environmental Science and Technology 45: 6697-6702.
Poeplau C., Don A., 2012. "Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe" in Geoderma 192: 189-201.
Poeplau C., Don A., Vesterdal L., Leifeld J., Van Wesemael B., Schumacher J., Gensior A., 2011. "Temporal dynamics of soil organic carbon after land-use change in the temperate zone - carbon response functions as a model approach" in Global Change Biology 17: 2415-2427.
Post W.M., Kwon K.C., 2000. "Soil carbon sequestration and land-use change: Processes and potential" in Global Change Biology 6: 317-327.
Powlson D. S., Smith P. , U. S.J. (1996) Evaluation of Soil Organic Matter Models: Using Existing Long-Term Datasets, Global Environmental Change.
Powlson D.S., Smith P., Coleman K., Smith J.U., Glendining M.J., Körschens M., Franko U., 1998. "A European network of long-term sites for studies on soil organic matter" in Soil and Tillage Research 47: 263-274.
Powlson, D. S., Whitmore, a. P., & Goulding, K. W. T. (2011). Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. European Journal of Soil Science, 62(1), 42–55. doi:10.1111/j.1365-2389.2010.01342.x
Prasanna R., Joshi M., Rana A., Shivay Y.S., Nain L., 2012. "Influence of co-inoculation of bacteria-cyanobacteria on crop yield and C-N sequestration in soil under rice crop" in World Journal of Microbiology and Biotechnology 28: 1223-1235.
Reeves, D. W. (1997). The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil and Tillage Research, 43, 131–167. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0031446526&partnerID=40&md5=7597e88c2348cbc19bab05e405feecde
Rodionov A., Nii-Annang S., Bens O., Trimborn M., Schillem S., Schneider B.U., Raab T., Hüttl R.F., 2012. "Impacts of Soil Additives on Crop Yield and C-Sequestration in Post Mine Substrates of Lusatia, Germany" in Pedosphere 22: 343-350.
Ruiz-Peinado R., Moreno G., Juarez E., Montero G., Roig S., 2013. "The contribution of two common shrub species to aboveground and belowground carbon stock in Iberian dehesas" in Journal of Arid Environments 91: 22-30.
Rytter R.M., 2012. "The potential of willow and poplar plantations as carbon sinks in Sweden" in Biomass and Bioenergy 36: 86-95.
Schapendonk A.H.C.M., Dijkstra P., Groenwold J., Pot C.S., Van Geijn S.C.D.E., 1997. "Carbon balance and water use efficiency of frequently cut Lolium perenne L. swards at elevated carbon dioxide" in Global Change Biology 3: 207-216.

Schils, R. (2008). Review of existing information on the interrelations between soil and climate change (CLIMSOIL) – Final Report. Contract number 70307/2007/486157/SER/B1:208. (R. (ed) Schils, Ed.). Brussels: European Commission. Retrieved from http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/climsoil_report_dec_2008.pdf

Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. a., … Trumbore, S. E. (2011). Persistence of soil organic matter as an ecosystem property. Nature, 478(7367), 49–56. doi:10.1038/nature10386

Schulte, R. P. O., Creamer, R. E., Donnellan, T., Farrelly, N., Fealy, R., O'Donoghue, C., & O'hUallachain, D. (2013). Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Environmental Science and Policy. doi:10.1016/j.envsci.2013.10.002

Schuman G.E., Janzen H.H., Herrick J.E., 2002. "Soil carbon dynamics and potential carbon sequestration by rangelands" in Environmental Pollution 116: 391-396.

Seufert, V., Ramankutty, N., & Foley, J. a. (2012). Comparing the yields of organic and conventional agriculture. Nature, 485(7397), 229–32. doi:10.1038/nature11069

Shrestha R.K., Lal R., Rimal B., 2013. "Soil carbon fluxes and balances and soil properties of organically amended no-till corn production systems" in Geoderma 197-198: 177-185.

Singh B.R., Lal R., 2005. "The potential of soil carbon sequestration through improved management practices in Norway" in Environment, Development and Sustainability 7: 161-184.

Six J., Ogle S.M., Breidt F.J., Conant R.T., Mosiers A.R., Paustian K., 2004. "The potential to mitigate global warming with no-tillage management is only realized when practised in the long term" in Global Change Biology 10: 155-160.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., … Smith, J. (2008). Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1492), 789–813. doi:10.1098/rstb.2007.2184

Smith, D., M., Cai, Z., Gwary, D., Janzen, H., Kumar, P., … O. Sirotenko, P. (2007). Agriculture. (O. R. D. B. Metz P.R. Bosch, R. Dave, L.A. Meyer, Ed.)Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., … O'Mara, F. (2007). Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agriculture, Ecosystems and Environment, 118(1-4), 6–28. doi:10.1016/j.agee.2006.06.006

Smith, P., & Falloon, P. (2005). Carbon sequestration in European croplands. SEB Experimental Biology Series, 47–55. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-34748821200&partnerID=40&md5=7d88c5626383c8b87ef83768d44c9346

Smith P., Andrén O., Karlsson T., Perälä P., Regina K., Rounsevell M., Van Wesemael B., 2005. "Carbon sequestration potential in European croplands has been overestimated" in Global Change Biology 11: 2153-2163.

Smith P., Falloon P., 2005. "Carbon sequestration in European croplands" in SEB experimental biology series 47-55.

Smith, P. (2004). Carbon sequestration in croplands: The potential in Europe and the global context. European Journal of Agronomy, 20(3), 229–236. doi:10.1016/j.eja.2003.08.002

Smith P., Goulding K.W., Smith K.A., Powlson D.S., Smith J.U., Falloon P., Coleman K., 2001. "Enhancing the carbon sink in European agricultural soils: Including trace gas fluxes in estimates of carbon mitigation potential" in Nutrient Cycling in Agroecosystems 60: 237-252.

Smith P., Milne R., Powlson D.S., Smith J.U., Falloon P., Coleman K., 2000a. "Revised estimates of the carbon mitigation potential of UK agricultural land" in Soil Use and Management 16: 293-295.

Smith P., Powlson D.S., Schlesinger W.H., 2000b. "Considering manure and carbon sequestration [4] (multiple letters)" in Science 287: 428-429.

Smith P., Powlson D.S., Smith J.U., Falloon P., Coleman K., 2000c. "Meeting Europe's climate change commitments: Quantitative estimates of the potential for carbon mitigation by agriculture" in Global Change Biology 6: 525-539.

Smith P., Powlson D.S., Glendining M.J., Smith J.U., 1997a. "Potential for carbon sequestration in European soils: Preliminary estimates for five scenarios using results from long-term experiments" in Global Change Biology 3: 67-79.

Smith P., Smith J.U., Powlson D.S., Mcgill W.B., Arah J.R.M., Chertov O.G., Coleman K., Franko U., Frolking S., Jenkinson D.S., Jensen L.S., Kelly R.H., Klein-Gunnewiek H., Komarov A.S., Li C., Molina J.a.E., Mueller T., Parton W.J., Thornley J.H.M., Whitmore A.P., 1997b. "A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments" in Geoderma 81: 153-225.

Soco, 2009. "Addressing soil degradation in EU agriculture: relevant processes, practices and policies. " in: report on the project Sustainable Agriculture and Soil Conservation (SoCo). Page, Luxembourg, European Communities.

Soderstrom, B., Hedlund, K., Jackson, L., Katterer, T., Lugato, E., Thomsen, I., & Bracht Jorgensen, H. (2014). What are the effects of agricultural management on soil organic carbon (SOC) stocks? Environmental Evidence, 3(1), 2. Retrieved from http://www.environmentalevidencejournal.org/content/3/1/2

Soussana J.F., Loiseau P., Vuichard N., Ceschia E., Balesdent J., Chevallier T., Arrouays D., 2004. "Carbon cycling and sequestration opportunities in temperate grasslands" in Soil Use and Management 20: 219-230.

Stavi I., 2013. "Biochar use in forestry and tree-based agro-ecosystems for increasing climate change mitigation and adaptation" in International Journal of Sustainable Development and World Ecology 20: 166-181.

Stavi, I., & Lal, R. (2013). Agroforestry and biochar to offset climate change: A review. Agronomy for Sustainable Development, 33(1), 81–96. doi:10.1007/s13593-012-0081-1

Stockmann, U., Adams, M. a., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., … Zimmermann, M. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems and Environment, 164(2013), 80–99. doi:10.1016/j.agee.2012.10.001

Strassburg B.B., Kelly A., Balmford A., Davies R.G., Gibbs H.K., Lovett A., Miles L., Orme C.D.L., Price J., Turner R.K., Rodrigues A.S., 2010. "Global congruence of carbon storage and biodiversity in terrestrial ecosystems" in Conservation Letters 3: 98-105.

Teixeira R.F.M., Domingos T., Costa A.P.S.V., Oliveira R., Farropas L., Calouro F., Barradas A.M., Carneiro J.P.B.G., 2011. "Soil organic matter dynamics in Portuguese natural and sown rainfed grasslands" in Ecological Modelling 222: 993-1001.

Thelen K.D., Fronning B.E., Kravchenko A., Min D.H., Robertson G.P., 2010. "Integrating livestock manure with a corn–soybean bioenergy cropping system improves short-term carbon sequestration rates and net global warming potential" in Biomass and Bioenergy 34: 960-966.

Thevathasan N.V., Gordon A.M., Price G.W., 2000. "Biophysical and ecological interactions in a temperate tree-based intercropping system in southern Ontario, Canada" in: Fourth Biennial Meeting, North American Chapter. (ed Association I.F.S.) Page, North America.

Thomsen I.K., Christensen B.T., 2010. "Carbon sequestration in soils with annual inputs of maize biomass and maize-derived animal manure: Evidence from 13C abundance" in Soil Biology and Biochemistry 42: 1643-1646.

Thornley J.H.M., Cannell M.G.R., 1997. "Temperate grassland responses to climate change: An analysis using the Hurley Pasture Model" in Annals of Botany 80: 205-221.

Thornley J.H.M., Fowler D., Cannell M.G.R., 1991. "Terrestrial carbon storage resulting from CO2 and nitrogen fertilization in temperate grasslands" in Plant, Cell & Environment 14: 1007-1011.

Titlyanova A., Rusch G., Van Der Maarel E., 1988. "Biomass structure of limestone grasslands on Oland in relation to grazing intensity" in Acta Phytogeographica Suecica 76: 125-134.

Tuittila E.S., Vasander H., Laine J., 2004. "Sensitivity of C sequestration in reintroduced Sphagnum to water-level variation in a cutaway peatland" in Restoration Ecology 12: 483-493.

Tuomisto, H. L., Hodge, I. D., Riordan, P., & Macdonald, D. W. (2012). Does organic farming reduce environmental impacts?--a meta-analysis of European research. Journal of Environmental Management, 112(834), 309–20. doi:10.1016/j.jenvman.2012.08.018

Turunen J., Tahvanainen T., Tolonen K., Pitkänen A., 2001. "Carbon accumulation in West Siberian mires, Russia" in Global Biogeochemical Cycles 15: 285-296.

Turunen J., Tomppo E., Tolonen K., Reinikainen A., 2002. "Estimating carbon accumulation rates of undrained mires in Finland - Application to boreal and subarctic regions" in Holocene 12: 69-80.

USDA. (2011). MANUAL OF BEST MANAGEMENT PRACTICES (BMPS) FOR AGRICULTURE IN NEW HAMPSHIRE. Agricultural Best Management Practices Task Force. New Hampshire Department of Agriculture, Markets, and Food Concord.

Van Kessel C., Horwath W.R., Hartwig U., Harris D., Luscher A., 2000. "Net soil carbon input under ambient and elevated CO2 concentrations: Isotopic evidence after 4 years" in Global Change Biology 6: 435-444.

Van den Putte, A., Govers, G., Diels, J., Gillijns, K., & Demuzere, M. (2010). Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture. European Journal of Agronomy, 33(3), 231–241. doi:10.1016/j.eja.2010.05.008

VandenBygaart, a. J., Gregorich, E. G., & Angers, D. a. (2003). Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies. Canadian Journal of Soil Science, 83(4), 363–380. doi:10.4141/S03-009

Venkateswarlu, B., Lal, R., Singh, A. K., Kundu, S., Vittal, K. P. R., Patel, J. J., & Patel, M. M. (2014). LONG-TERM MANURING AND FERTILIZER EFFECTS ON DEPLETION OF SOIL ORGANIC CARBON STOCKS UNDER PEARL MILLET-CLUSTER BEAN-CASTOR ROTATION IN WESTERN INDIA Details of the Experimental Location, 183(December 2011), 173–183.

Verheijen F.G.A., Jeffery, S., Bastos, A.C., Van Der Velde, M., and Diafas, I., 2009. "Biochar Application to Soils - A Critical Scientific Review of Effects on Soil Properties, Processes and Functions" (ed En E.) Page, Office for the Official Publications of the European Communities, Luxembourg, EC.

Walter C., Merot P., Layer B., Dutin G., 2003. "The effect of hedgerows on soil organic carbon storage in hillslopes" in Soil Use and Management 19: 201-207.

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. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0036850951&partnerID=40&md5=6f82a267ffa4b9f0b26089cb19238ccf

White Em, Krueger Cr, Ra M., 1976. "Changes in Total N, Organic matter, available P, and bulk densities of a cultivated soil 8 years after tame pastures were established" in Agronomy Journal 68: 581-583.

White, P. J., Crawford, J. W., Díaz, Á. M. C., & Moreno, R. G. (2012). Soil Management for Sustainable Agriculture. Applied and Environmental Soil Science. doi:10.1155/2012/850739

Woolf D., Amonette J.E., Street-Perrott F.A., Lehmann J., Joseph S., 2010. "Sustainable biochar to mitigate global climate change" in Nature Communications 1:

Chapter IV

EU soil organic carbon databases integration through a modelling approach: the Veneto case study

Introduction

At international level, in the framework of the UNFCCC negotiations, the debate on reductions of GHGs emissions from Land Use, Land Use Changes and Forestry (LULUCF) activities was largely restricted to deforestation and forest degradation (UN, 1997; IPCC, 2007). While the regulations and the accounting on agricultural lands – cropland and grassland- is not mandatory, many studies aim to include the GHGs emissions from agricultural soils in the estimates of the mitigation potential (Smith *et al.*, 2005a). Land cover changes due to human activities, resulting in, changes in biophysical attributes of the soil and in land management, are fundamental issues for EU policy makers and ecosystem planners. The obligations associated with various legislations could considerably influence SOC levels. The capability of monitoring those changes is linked to the availability of information on the coverage and the use of the land.

At EU level LULUCF activities have been acknowledged but not fully implemented(EC, 2012c, 2012d, 2012e), losing the opportunity to implement measures able to offset GHG emissions especially for cropland management (Lantz *et al.*, 2001; Eaton *et al.*, 2008; Smith *et al.*, 2008a; Wang *et al.*, 2011). However the EU is generally concerned by the lack of potentially useful data to drive the preparation of climatic and agricultural policies. Stock changes of OM in agricultural soils and the request of increasing current level of OM by 2020 are broadly argued (EC, 2006b, 2012a; Schils, 2008, EC, 2011).

Currently, data available at pan-European level are: (a) the estimation of SOC content done by Jones *et al.*, 2005 and based on soil data coming from the 1980-90s; (b) the SOC data supplied from the EIONET-SOIL network and discussed in chapter 2 (Panagos *et al.*, 2013a; EC, 2014); (c) the recent LUCAS 2009 survey, introduced as well in chapter 2 and used in this chapter. All these information are static, lacking of geo-referenced, measured and not harmonised data are available from systematic sampling programmes. Only the recent LUCAS 2009 soil survey represents the first attempt of a harmonised monitoring system. For this reason it is difficult to implement and provide support to the policy makers with future scenario analysis (Lugato *et al.*, 2014a).

Batjes, (2011), proposed, a standardized system for sustainable land management projects to measure, model and report changes in C stocks and GHG emissions for use at varying scales[21]. The IPCC-Good Practice Guidelines (GPG) identifies three levels or tiers of complexity that can be used to calculate GHG emissions. The IPCC GPG provides a standard or default method to estimate GHG emissions from various sectors and activities. Tier 1 is based on default values derived from international research. The highest Tier, level 3, is based on advanced scientific analysis research relevant to that country. The models involved are country specific, adapted to yield a more accurate representation of the GHG activity within the country. Tier 3 methods involve the development of an advanced forecasting system, incorporating process-based models such as RothC or Century (Milne *et al.*, 2007) to better represent the seasonal or annual variability in C dynamics and GHG fluxes.

Following the IPCC GPG suggested (IPCC, 2000, 2006) on a Tier 3 approach (i.e. higher order method) a modelling exercise to create a pan-European platform has been developed for the CAPRESE project where measured datasets have been used for validating the model (Lugato *et al.*, 2014a). Subsequentely, the platform has been used to simulate the long term effects of natural (i.e. climatic and environmental) and human (i.e. land management) drivers on SOC changes due to alternative practices adopted in the long term (Lugato *et al.*, 2014a, 2014b).

Several studies have evaluated the capacities of the different modifications in land use and land management to increase the SOC stocks. However, these studies do not explicitly relate SOC enhancement measures to diversity of soil types. In the EU several models have been used for SOC predictions at different scales: in Smith *et al.*, (2005) the scale was continental; for van Wesemael *et al.*, (2010), Oelbermann & Voroney, (2011), Mondini *et al.*, (2012), De Gryze *et al.*, (2011), Bortolon *et al.*, (2011) and Álvaro-Fuentes *et al.*, (2011) the scale was respectively regional and sub-regional; for (Smith *et al.*, 1997b; Lugato *et al.*, 2007; Lugato & Berti, 2008; Wattenbach *et al.*, 2010) the prediction were for specific LTEs. Many studies estimated soil C balance at global and EU scale under different climatic scenarios, but only a few of them (Morales *et al.*, 2005; Smith & Falloon, 2005; Lugato & Berti, 2008) considered the effect of management practices for sequestering C in the soil (Lal, 2004a; Lal *et al.*, 2004; Smith,

[21] Under the Carbon Benefits Project (CBP), co-funded by the Global Environmental Facility (GEF) and executed in turn by the United Nations Environment Programme (UNEP)

2004c). The European Commission indicated a need to synthesise the existing knowledge on the SOC dynamics in agricultural soils with a view to developing a methodology for identifying potential target areas and the magnitude for potential changes in SOC stocks over time (Schils, 2008; EC, 2009a). Starting from the work developed in the contest of the CAPRESE project at pan European scale (EU + Serbia, Bosnia and Herzegovina, Montenegro, Albania, Former Yugoslav Republic of Macedonia and Norway) of Lugato *et al.*, 2014a, 2014b, this chapter will focus on the implementation of this approach at regional scale for the Veneto region.

The agro-ecosystem model CENTURY (Parton *et al.*, 1988, 1994; Parton, 1996; Shaffer *et al.*, 2001) permitted to calculate the SOC stocks for 2479 uses combinations of soil, climate, land use and management change to assess SOC fluxes. The land uses taken into consideration included cropland and grasslands. The practices selected reflect the current and the historical management Veneto Region (i.e. mineral and organic fertilization, irrigation, tillage, etc.) and were derived from Veneto region statistics and literature.

The results have been compared with three different soil inventories providing SOC measured data: the soil survey exercise LUCAS 2009 at EU level, the soil survey personally carried on in 2011 (named LUCAS 2011) and the data coming from ARPAV. The data coming from LUCAS 2009 and LUCAS 2011 are considered the start point t0 and the t1 has been estimated through the agro-ecosystem model. A further comparison has been done with the EIONET-SOIL inventory previously discussed in chapter 2 (Panagos *et al.*, 2013a; EC, 2014).

The aim of the chapter is, through an integration of the existing SOC databases and the use of a simulation model, to estimate the actual values of SOC and to model the implementation of the most promising selected management practices in two different climatic scenarios in Veneto Region.

Materials and methods

Model

There are several models that permit spatial simulation of the evolution of soil C levels due to land use changes (Smith *et al.*, 1997c; FAO, 2001, 2004) and the effects of climate change (Lal *et al.*, 1997). The two most commonly used models are CENTURY (Parton *et al.*, 1988, 1994; Parton, 1996) and DNDC (Li *et al.*, 1997). Both models require climate data (i.e. temperature and precipitation), soil characteristics and information on land management. Other models are: RothC-26-3 set up during the Rothamsted experiments for OM turnover in temperate regions (Jenkinson & Rayner, 1977; Coleman *et al.*, 1997; Jenkinson & Coleman, 2008) and the ICBM model (Kätterer *et al.*, 2004).

This thesis assess the impacts of management and climate on SOC storage and dynamics at regional level with CENTURY model because of his long-term trends as the SOC pool could take even 100 years to reach a new equilibrium (Paustian *et al.*, 1997); the sensitivity to change in different land management options and climate (Smith *et al.*, 1997b) and because of previous studies run in the same area (Lugato *et al.*, 2007; Lugato & Berti, 2008).

The CENTURY SOM Model Environment (version 4.0) is an agri-ecosystem model that simulates the long-term dynamics of Carbon (C), Nitrogen (N), Phosphorus (P), and Sulphur (S), primary productivity and water balance for different plant-soil systems at monthly steps. The model can simulate the dynamics of grassland systems, agricultural crop systems, forest systems, and savannah systems. The grassland/crop and forest systems have different plant production sub-models which are linked to a common SOM sub-model. The SOM sub-model simulates the flow of C, N, P, and S through two plant litter fractions (i.e. metabolic and structural) and the different inorganic and organic pools in the topsoil (i.e. active, slow and passive) differing in decomposability and in the degree of turnover rates. Soil temperature and moisture, soil texture and cultivation practices have different effects on these rates (Parton *et al.*, 1988, 1994; Parton, 1996; Shaffer *et al.*, 2001).

The model uses a monthly time step and the major input variables include:

- monthly average maximum and minimum air temperature;
- monthly precipitation;
- lignin content of plant material;
- plant N, P, and S content;
- soil texture;
- atmospheric and soil N inputs;
- initial soil C, N, P, and S levels (Parton *et al.*, 1988).

The model includes three SOC pools (*Active organic C, Slow Organic C* and *Passive Organic C* respectively in Figure 4.1) with different potential decomposition rates, above and belowground litter pools (*Aboveground and Belowground* in Figure 4.1) and a surface microbial pool (*Surface Microbe* C in Figure 4.1) which is associated with decomposing surface litter (Parton *et al.*, 1988, 1994; Parton, 1996).

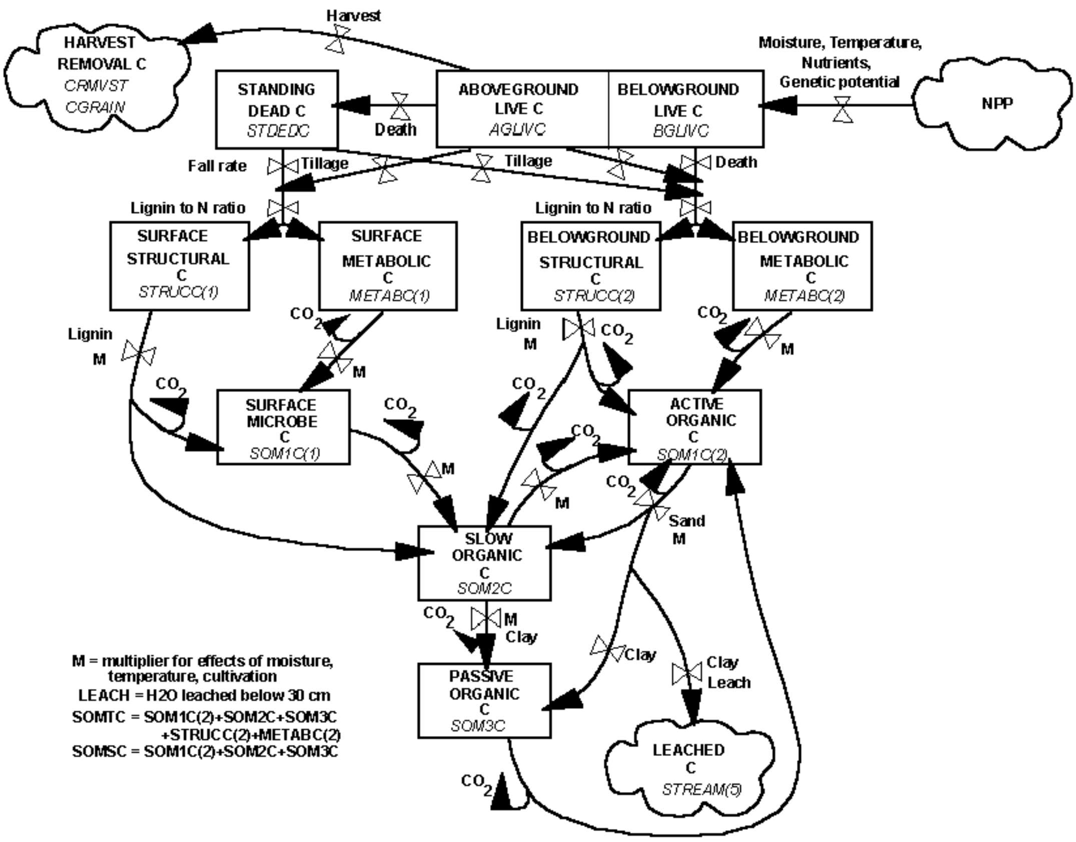


Figure 4.1 Flow diagram for the SOM sub-model CENTURY (Parton *et al.*, 1988, 1994; Parton, 1996).

Figure 4.1 describes the three different pools:

- The **active pool** (SOM1C(2)) represents soil microbes and microbial products (total active pool is from 2 to 3 times the live microbial biomass level) and has a turnover time of months to a few years depending on the environment and sand content of the soil. Soil texture influences the turnover rate of the active soil SOM (higher rates for sandy soils) and the efficiency of stabilizing active SOM into slow SOM (higher stabilization rates for clay soils). The surface microbial pool (SOM1C(1)) turnover rate is independent of soil texture and it transfers material directly into the slow SOM pool.
- The **slow pool** (SOM2C) includes resistant plant material derived from the structural pool and soil-stabilized microbial products derived from the active and surface microbe pools. It has a turnover time of 20 to 50 years.
- The **passive pool** (SOM3C) is very resistant to decomposition and includes physically and chemically stabilized SOM and has a turnover time of 400 to 2000 years. The proportions of the decomposition products which enter the passive pool from the slow and active pools increase with increasing soil clay content (Parton *et al.*, 1988, 1994; Parton, 1996).

In order to run CENTURY different input variables have been collected and linked though the ArcGIS 10.2 platform, TextPad, Notepad++ and R-project.

Data sets

The data framework used by the model is represented by 2479 polygons derived from the overlay of three different spatial layers: initially **soil** data with a **climate** grid . And in a second step information on **land use**.

Soil data

Information on the spatial distribution of soil properties is derived from the ARPAV database related to the Veneto Region soil map, 1:250,000 scale[22].

The soil map it is based on the World Reference Base for Soil Resources (WRB) - FAO 1998 classification system and it follows the following structure:

- L1 SOIL REGIONS: "regioni", containing information on climate and parent material
  - L2 SOIL SUBREGIONS: "province"
    - L3 GREAT SOILSCAPES: "sistema di suoli"
      - **L4 SOILSCAPES**: "sottosistema di suoli" – this is the level used by this study and specifically by the CENTURY model implementation

Only the first horizon "A" horizon or topsoil layer was modelled by the CENTURY model. The model, originally parameterized for the 0–20 cm depth, was modified to simulate the 0–30 cm layer (Álvaro-Fuentes *et al.*, 2011). For each L4 soilscapes there is information on: horizons thickness, drainage class, soil texture, BD, $CaCO_3$, pH, carbon and coarse fragments. The drainage classes in the Veneto soil map are referring to the FAO classification where the classes range goes from 1 to 7.

Regarding the soil texture: sandy soils (>45%) are found in the area of Adige river, along the coast and in some areas of Treviso and Vicenza provinces. Almost all of the soils of the Low Plain have high levels of silt (30-45%). Clay soils (>45%), derived from basalts are mostly found in the pre-Alps of Verona and Vicenza provinces, in some low lying land areas or reclaimed areas.

CENTURY has a simple water bucket model, in order to estimate the hydraulic properties (field capacity and wilting point) the PTR of Rawls (Rawls *et al.*, 1982) were used and these two parameters were corrected for the presence of rock according to the factor:

$$[1- (Rv/100)]$$

where Rv is the rock fragment content by volume.

Treviso province, in the High Venetian Plain, is rich in coarse texture, sometimes with more than 35%. As well, the high plain in Vicenza and Padova plain are rich in coarse due to the conoid area of the Brenta river

---

22 Project *Carta dei suoli d'Italia* and publications *Carta dei Suoli del Bacino Scolante della Laguna di Venezia* and *Carta dei Suoli del Veneto*

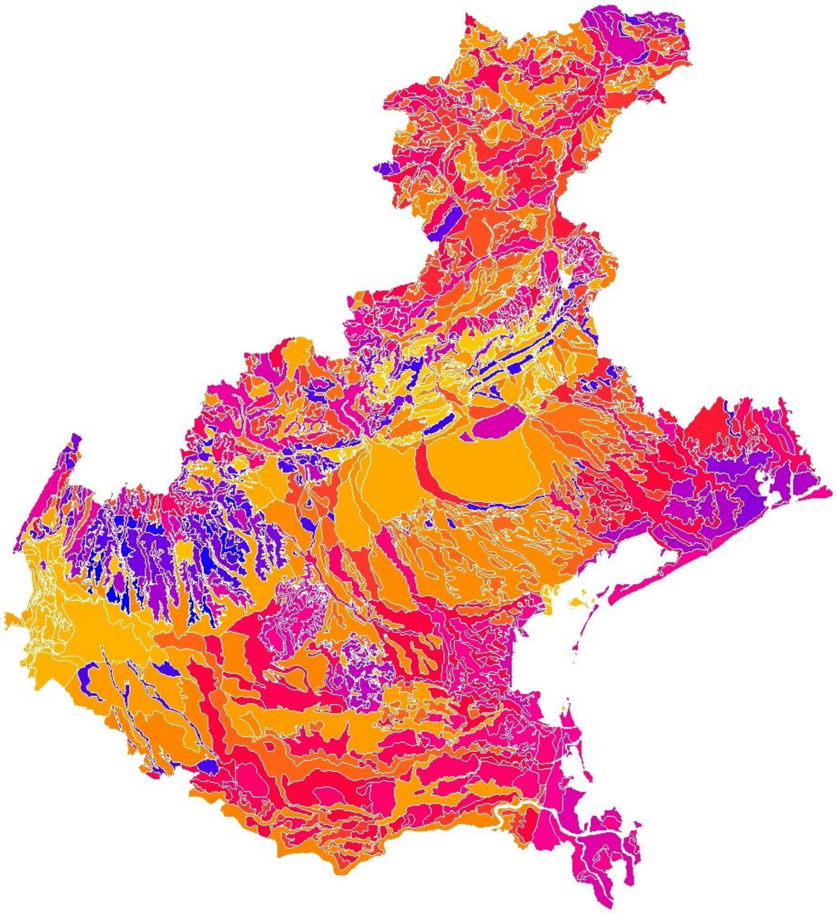


Figure 4.2 Soil polygons (the different colours show only the different soil types, no specifically legend attached).

Climatic data

The ecosystem productivity and SOC dynamics are strongly influenced by climatic and environmental conditions. Monthly temperature (i.e. Tmax and Tmin) and monthly precipitation data for Veneto Region were extracted from the CRU TS 1.2 [23] grid (for the range 1901–2000 – actual data) and TYN[24] SC 1.2 (for the range 2001–2100 – climate projection) European climate databases at a 10´ × 10´ resolution, downloaded from the Climate Research Unit of the University of East Anglia (CRU TS 1.2)[25]. In the CRU TS 1.2 monthly grids dataset there are five climatic variables available: cloud cover, DTR, precipitation, temperature, vapour pressure (see table 4.1).

[23] Climatic Research Unit
[24] Tyndall Centre for Climate Change Research
[25] http://www.cru.uea.ac.uk/cru/data/hrg/

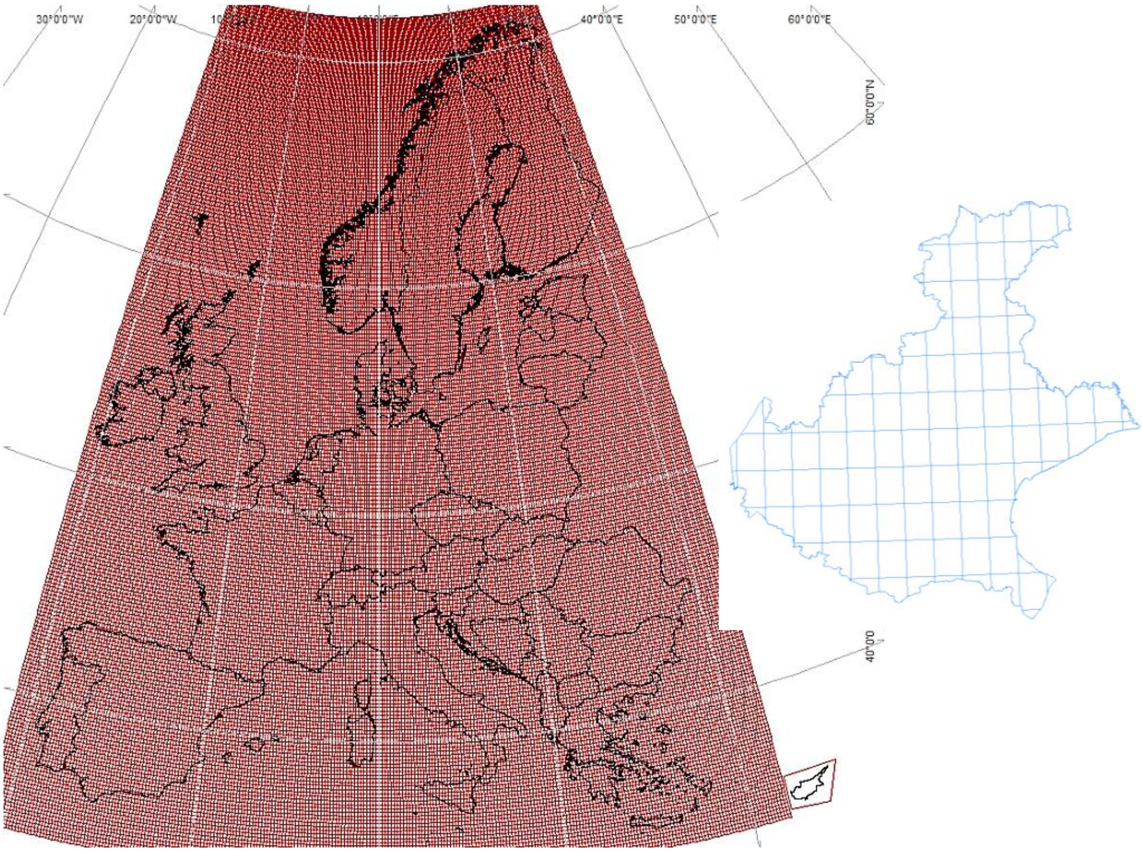


Figure 4.3 Extent of the Tyndall grid for the EU and for the Veneto Region

Table 4.1 Information on the CRU TS 1.2 and the TYN SC 1.0 datasets

dataset	space	time	variety	variables	reference
CRU TS 1.2	10' Europe	1901-2000	time-series	pre, tmp, dtr, vap, cld	(Mitchell *et al.*, 2004)
TYN SC 1.0	10' Europe	2001-2100	scenarios	pre, tmp, dtr, vap, cld	(Mitchell *et al.*, 2004)

In order to assess future SOC variations the General Circulation Models (GCMs) have been used to project the main variables driving the SOC balance (e.g. temperature, precipitation, CO_2). The monthly climate data for the range 2001–2100 for Veneto Region were extracted using outputs from two different GCMs models scenarios, namely HadCM3_A1FI and PCM-B1. The two models are forced by two different CO_2

emissions scenarios as defined in the IPCC in the Special Report on Emissions Scenarios (SRES)[26]:

- HadCM3_A1FI "world markets fossil fuel intensive"
- PCM_B1 "global sustainability"

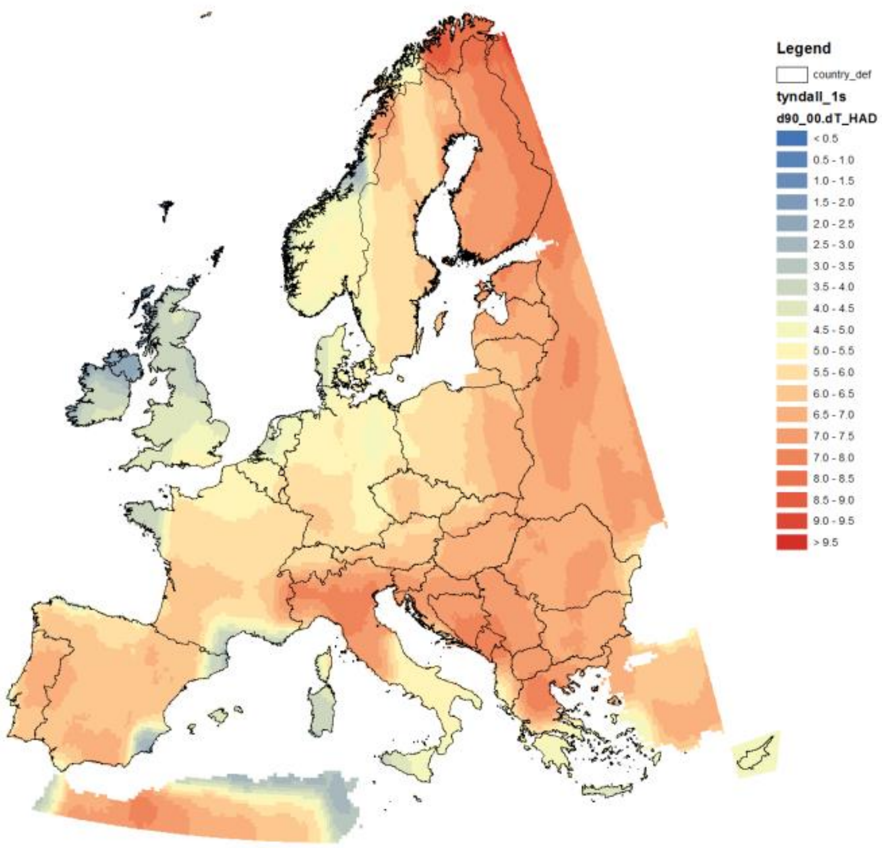


Figure 4.4 GCM scenario **HAD3_AIF1** forced with IPCC emissions: Δ Temperature in °C (2090_2100-1990_2000) for EU.

.

[26] http://www.ipcc-data.org/sim/gcm_global/index.html

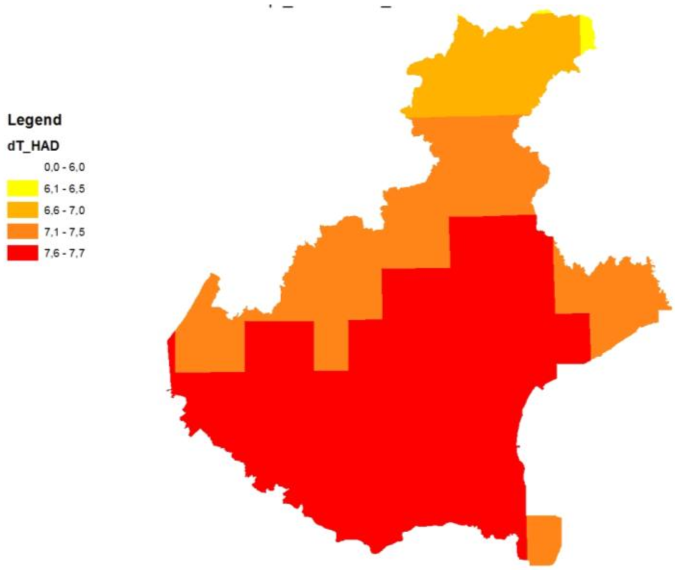


Figure 4.5 GCM scenario **HAD3_AIF1** forced with IPCC emissions: Δ Temperature in °C (2090_2100-1990_2000) for Veneto Region

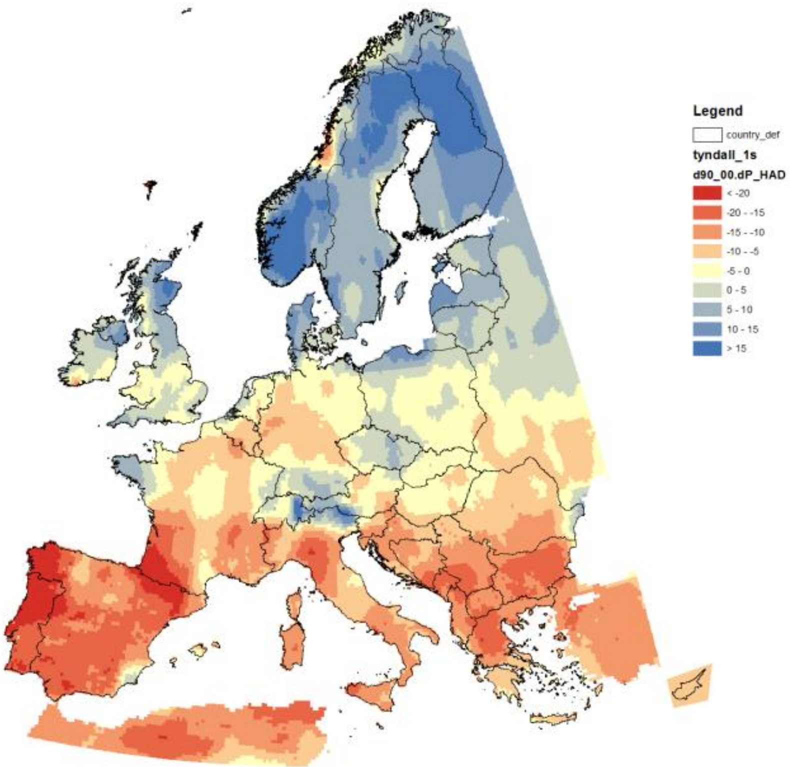


Figure 4.6 GCM scenario **HAD3_AIF1** forced with IPCC emissions: Δ Precipitation in mm (2090_2100-1990_2000) for EU.

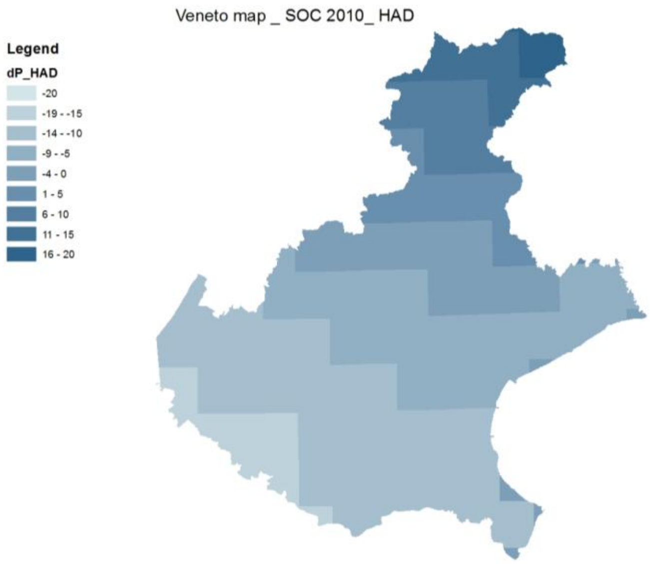


Figure 4.7 GCM scenario **HAD3_AIF1** forced with IPCC emissions: Δ Precipitation in mm (2090_2100-1990_2000) for Veneto Region.

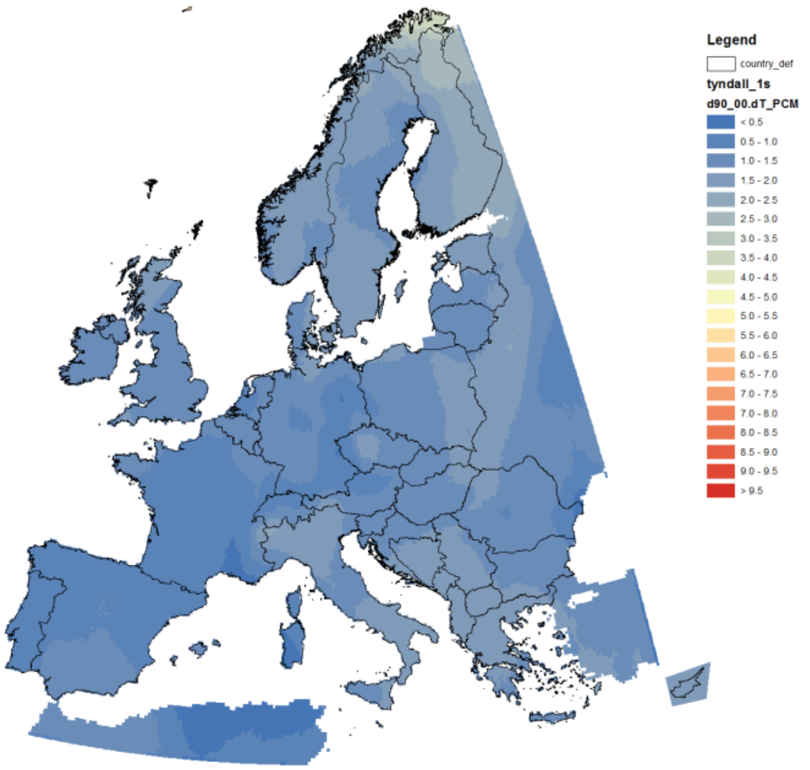


Figure 4.8 GCM scenario **PCM_B1** forced with IPCC emissions: Δ Temperature in °C (2090_2100-1990_2000) for EU.

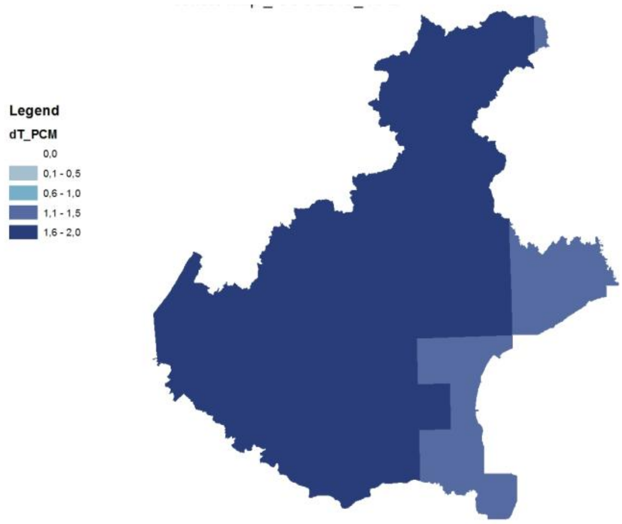


Figure 4.9 GCM scenario **PCM_B1** forced with IPCC emissions: Δ Temperature in °C (2090_2100-1990_2000) for Veneto Region.

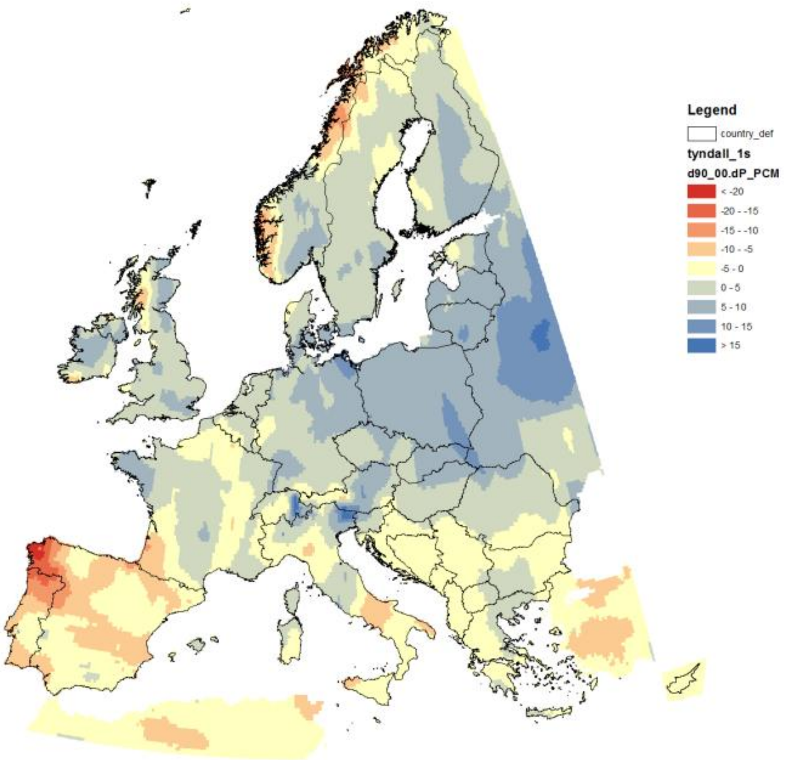


Figure 4.10 GCM scenario **PCM_B1** forced with IPCC emissions: Δ Precipitation in mm (2090_2100-1990_2000) for EU

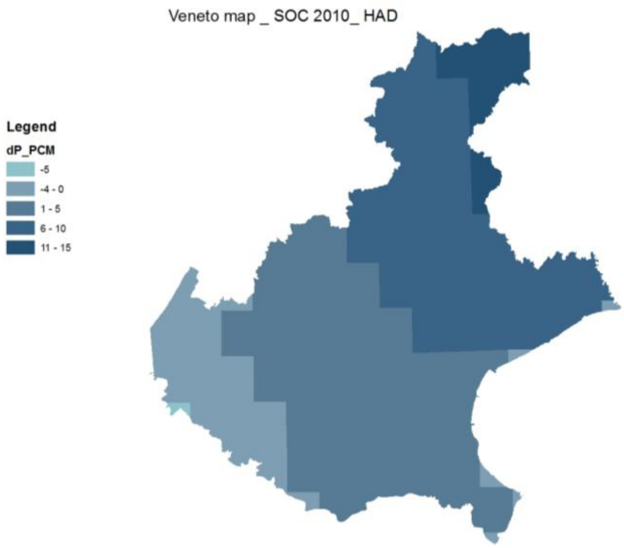


Figure 4.11 GCM scenario **PCM_B1** forced with IPCC emissions: Δ Precipitation in mm (2090_2100-1990_2000) for Veneto Region

Land cover and land use data

The information on land use classes are derived from the Corine Land Cover (CLC) databases for the years 1990, 2000 and 2006 with specific focus on agricultural areas[27].

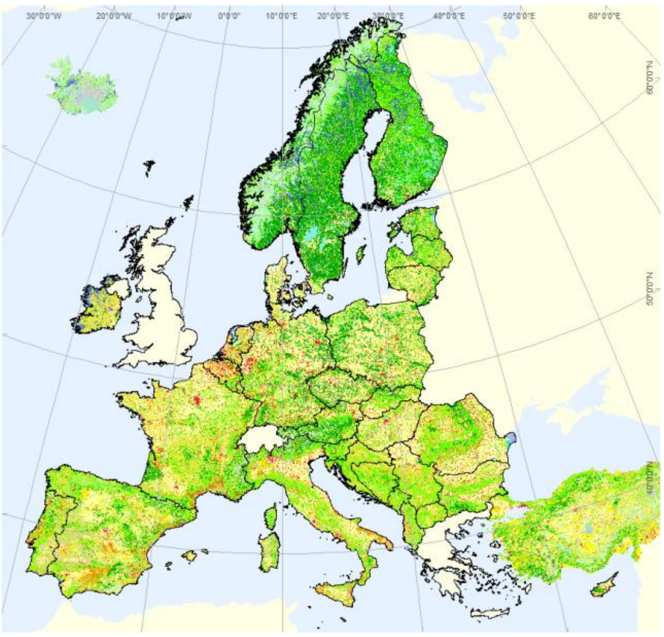


Figure 4.12 100m resolution land over vector map[28] for Europe, 1:100 000. For legend refer to table 4.2

[27] CORINE Land Cover 2000&2006 http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000

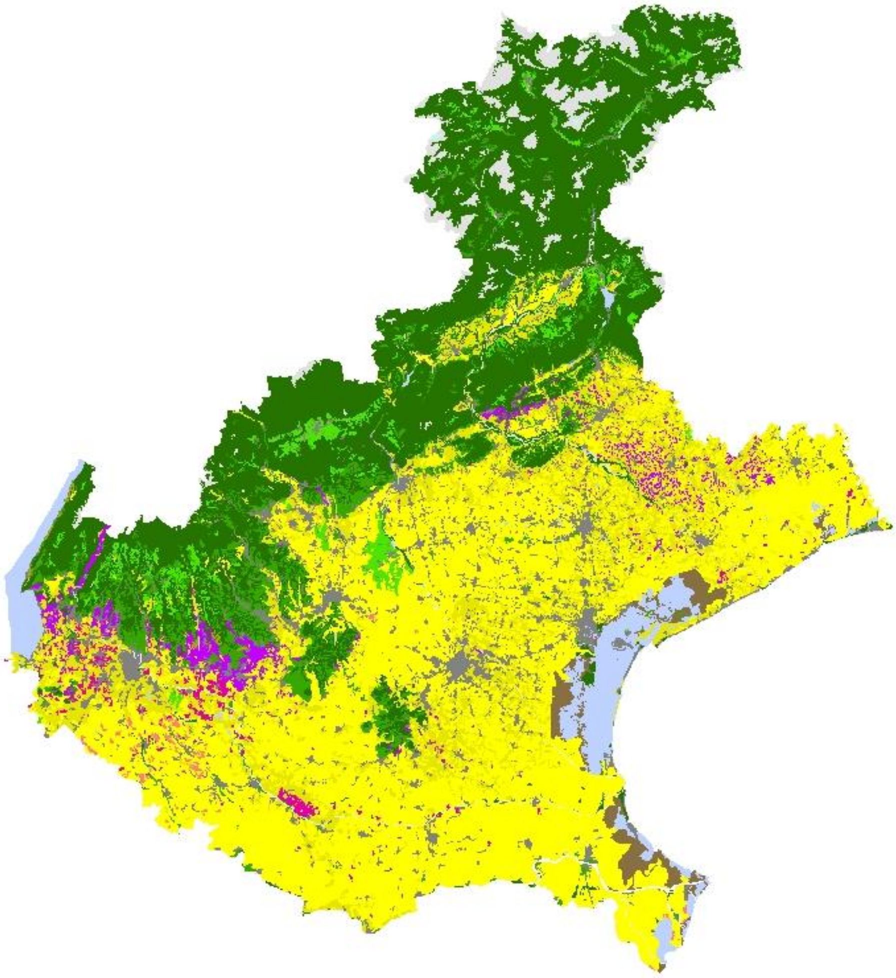


Figure 4.13 CLC for Veneto Region 2006. Legend in Table 4.2.

The land cover changes taken into consideration refer to 1990, 2000 and 2006 and only the category agricultural areas was considered:

- 211 non irrigated arable lands - CLC definition[29]: “Cereals, legumes, fodder crops, root crops and fallow land. Includes flower and tree (nurseries) cultivation and vegetables, whether open field, under plastic or glass (includes market gardening). Includes aromatic, medicinal and culinary plants. Excludes permanent pastures”.
- 213 rice fields
- 221 vineyards

[28] http://www.eea.europa.eu
[29] http://www.eea.europa.eu/publications/COR0-landcover/at_download/file

CLC_CODE		LEVEL1	LEVEL2	LEVEL3
111 - 112		Artificial surfaces	Urban fabric	Continuous urban fabric and Discontinuous urban fabric
121 – 122 -123- 124			Industrial, commercial and transport units	Industrial or commercial units, Road and rail networks and associated land, Port areas, Airports
131-132-133			Mine, dump and construction sites	Mineral extraction sites ,Dump sites, Construction sites
141 - 142			Artificial, non-agricultural vegetated areas	Green urban areas, Sport and leisure facilities
211		Agricultural areas	Arable land	Non-irrigated arable land
213				Rice fields
221			Permanent crops	Vineyards
222				Fruit trees and berry plantations
223				Olive groves
231			Pastures	Pastures
241			Heterogeneous agricultural areas	Annual crops associated with permanent crops
242				Complex cultivation patterns
243				Land principally occupied by agriculture, with significant areas of natural vegetation
311		Forest and semi natural areas	Forests	Broad-leaved forest
312				Coniferous forest
313				Mixed forest
321			Scrub and/or herbaceous vegetation associations	Natural grasslands
322				Moors and heathland
324				Transitional woodland-shrub
331			Open spaces with little or no vegetation	Beaches, dunes, sands
332 - 333 - 335				Bare rocks, Sparsely vegetated areas ,Glaciers and perpetual snow
411- 421- 422- 423		Wetlands	Inland and maritime wetlands	Inland marshes, Salt marshes, salines, Intertidal flats
511- 512- 521		Water bodies	Inland and maritime waters	Water courses and bodies, coastal lagoons

Table 4.2 CLC levels present in Veneto Region.

- 222 fruit trees and berry plantations
- 223 olive groves
- 231 pastures - CLC definition: "Dense, predominantly graminoid grass cover, of floral composition, not under a rotation system. Mainly used for grazing, but the fodder may be harvested mechanically. Includes areas with hedges".
- 241 annual crops associated with permanent crops - CLC definition: "Non-permanent crops (arable lands or pasture) associated with permanent crops on the same parcel".
- 242 complex cultivation patterns - CLC definition: "Juxtaposition of small parcels of diverse annual crops, pasture and/or permanent crops".
- 243 land principally occupied by agriculture with significant natural vegetation - CLC definition: "Areas principally occupied by agriculture, interspersed with significant natural areas".

In Veneto Region there are only two little polygons representing code 244 (agroforestry). For this study the code 243 has been used to represent suitable areas to implement agroforestry as practice to promote SOC sequestration.

In the CLC classification code 321 represents natural grasslands. For this study the areas under this code has not been taken into account because as they represent low productivity grasslands often situated in areas of rough uneven ground and not considered by the agricultural sector.

For the management practices scenario codes 211 and 241 are treated the same and 242 partially the same with temporary forage inclusion.

Comparing the three CLC maps in Figure 4.14, interesting are the land use changes from 1990 to 2000 and from 2000 to 2006. The Istat agriculture census confirmed a lost in UAA between 1970 and 2010 mainly close to the main cities and in the industrial areas of Treviso and Vicenza provinces. Clearly visible are also the settlement concentrations that have developed along the main roads and highways. Italy is the fourth highest EU country for soil consumption and in the Veneto region, in 2010, about 2100 km^2 has been sealed (11.3 % of the Region). The Veneto, together with Lombardy and Campania regions, is considered as having one of the largest sealed surfaces in Italy (E. A. C. Costantini, 2013).

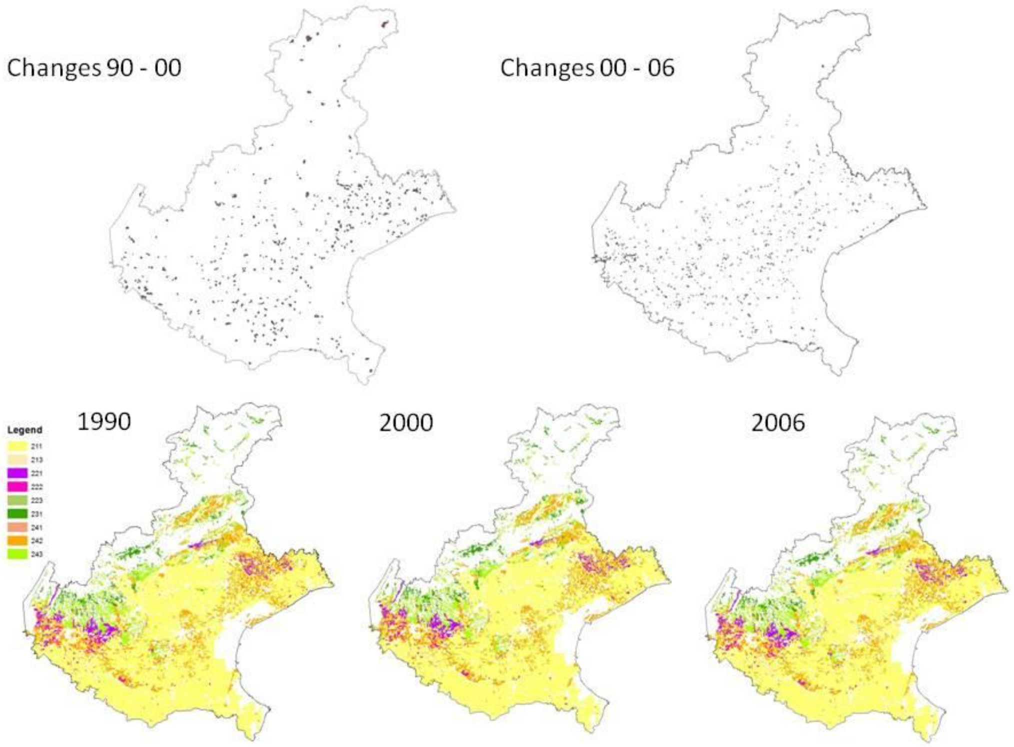


Figure 4.14 the three CLC reflecting years 1990, 2000 and 2006 and the respective changes for Veneto Region.

Table 4.3 Farm Structure Survey 2010 (ARPAV Veneto statistics[30]).

Provinces	Arable lands	Vineyards	Olive	Fruit trees	Grasslands	Forest
Verona	97.067,73	27.812,76	3.470,87	16.029,37	27.686,34	14.253,80
Vicenza	52.846,18	8.491,03	696,42	731,19	31.153,12	15.171,18
Belluno	4.431,06	56,64	23,45	190,77	42.172,60	39.401,42
Treviso	79.840,90	28.626,06	424,88	1.038,18	17.499,32	11.741,34
Venezia	101.633,74	6.631,34	111,24	1.014,18	1.635,37	1.196,15
Padova	119.578,86	5.901,96	430,99	1.311,67	9.351,59	5.642,64
Rovigo	113.860,78	365,67	22,13	2.194,10	1.038,16	461,83
TOT	**569.259,25**	**77.885,46**	**5.179,98**	**22.509,46**	**130.536,50**	**87.868,36**

Istat statistics for cropland (i.e. 211 and 241, partially 242) in the Veneto Region, Table 4.3., confirm limited changes during the past 30 years (-‘80s – 2010) crop production:

[30] http://statistica.regione.veneto.it/banche_dati_economia_agricoltura_db_2010.jsp

more than two thirds of the UAA (Utilised Agricultural Area) is currently committed to arable land, only grasslands and pastures decreased from 21% in 1982 and to 16% in 2010.

Also vineyards coverage, code 221, are stable, representing 75% of the woody crop, and are stable with the 15,7% of the UAA in Verona and 9,7% in Treviso (Veneto, 2013).An ArcGIS function has been utilized to extract the data layers for the Veneto Region and to link the meteorological layer, the soil layer and the land use layer, resulting in **7796 polygons:**

soil mapping unit / climate layer / land use (**SCL**)

Each SCL polygon would present a similar codification:

132_68_RVT3CAE1_211_242_242

where 132_68 is the grid climate code, RVT3CAE1 is the L4 soilscape and 211_242_242 is the sequence of CLC changes (i.e. from non irrigated arable land in 1990 to complex cultivation patterns in both 2000 and 2006).

The area for each specific category (e.g. arable lads, rice, orchard, etc.) was calculated for each SCL unit, the total are of the 7796 SCL polygons corresponds to 1043743 ha.

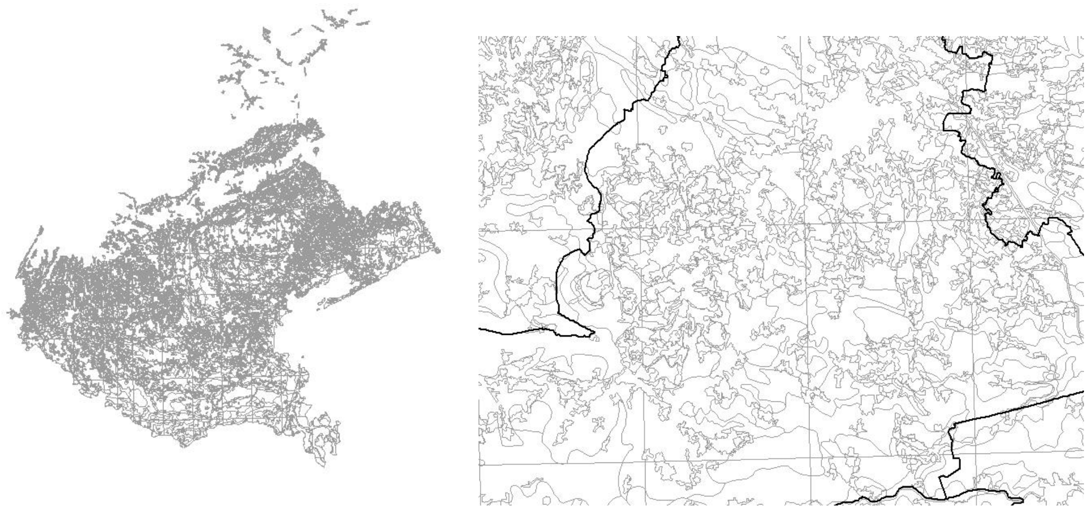


Figure 4.15 Overview of the 7796 SCL polygons for the Veneto region, equal to 10437 kmq and an inset showing detail.

Land management data

As regard to the Veneto, land management information and data on cropland (distribution and ratio), cropping systems, fertilizers, and irrigation systems have been collected from the past through literature review and from existing statistics.

Land management in Italy has a long history and reflects the occupation of the country by different populations. In general Italian soils through millennia of soil management passed from phases of intense and devastating exploitation to periods of reclamation and care. Recently with the challenges of the global market many agricultural soils, previously of good quality, are no longer competitive and are abandoned or extensively used. The traditional management of agricultural soils was based on equilibrium between the fertility subtracted from the soil and the fertility given back to the soil. During the Middle Ages and the Renaissance periods, agriculture was sustainable because the systems were a combination of crops and cattle breeding, for example one hectare of cereal crop was fertilised by the manure obtained by several hectares of grazing land (E. A. C. Costantini, 2013).

In the following paragraph on the methodology model spin-up each block will describe the management referring to a particular historical period, ranging from:

- Protohistory (including Iron Age), Classic Age, Middle Ages, Renaissance (XVI century) and Modern Age - 1st phase
- Risorgimento and Unification of Italy (1861) – 2nd phase.

The difficulty or impossibility to find information about soil management for historical periods should be noted (E. A. C. Costantini, 2013).

Model spin-up methodology

In the model implementation phase the procedure used to estimate the initial distribution of SOC is to simulate a long-period of land use history thus allowing the model to "self initialize" (Parton *et al.*, 1994; Paustian *et al.*, 2002; Lugato *et al.*, 2007)

The first part of the model spin-up methodology is based to the work done at European level in Lugato *et al.*, 2014a where a baseline of OC stock has been established for agricultural soils.

For each **SCL** combination the initial C content of the different SOC pools and the annual plant addition to the soil were obtained by running the CENTURY model to equilibrium using:

- average climate data
- clay content and SOC content values provided by the Veneto Region database.

Between years 0 and 2000, **824** soil/climate simulations were run in order to create an actual management representing a Business As Usual (BAU) scenario, based on the predicted climate and land use data.

The complex spin-up process was run for 2000 years; the sequences were simulated in each polygon.

Due to the difficulty to reconstruct precise past land use for the Veneto Region, some basic assumptions has been made for the past:

- the actual cultivated areas at present were likely to have been cultivated in the past continuously (Lugato *et al.*, 2014a);
- extensive European deforestation was assumed from 1000.

1st equilibrium sequence (EQUIL. 1)

The fists equilibrium sentence, as shown in Table 4.7, covered 1700 years.

The initial starting crop is mixed grass, after it has been inserted a typical 3-years rotation with wheat-oats and a fallow period called "*maggese*"[31], dedicated to recover the soil fertility and specifically SOM content.

Historically a 2-years rotation[32] was common (i.e. maggese and winter cereal -for example wheat-, plus *arbustum gallicum* vineyards) and a 4-years rotation "Tarello" or "*maggese degradato"* (i.e. one year of *maggese*, one year of grain crop and two years fallow[33]), crop areas were not widespread, with low yields in favour of more extensive pasture. Between VIII and X centuries was common the 3-years rotation "*Carlo Magno*" were the land was ploughed for the first time in June, then in September before the winter cereals. A side of the field was sown in autumn with rye, wheat or other winter cereals and another part of the field was sown in spring with spring oat or barley, each 3 years

[31] Maggese from Latin *maius*: in May the fallow field was tilled
[32] Senofonte, Tefrasto and Virgilio mention.
[33] Loietto in Italy

one part of the land was in maggese. In this way the time of fallow land was reduced (Scarpa, 1963).

During the Middle Ages, agriculture passed through a period of stagnation that brought back the fallow pasture. Only in the sixteenth century yields started to increase thanks to the crop rotations (Giardini, 2004).

2nd equilibrium sequence (EQUIL. 2)

In the mid-1700s an agricultural revolution started and a 4-years rotation, known as the *Norfolk rotation,* started to be implemented initially in Holland and Great Britain and later across all Europe (Scarpa, 1963).

In this second phase, which lasted around 300 years, an N-fixing crop (e.g. legumes, clover, etc.) has been introduced and the crop rotation systems were equally divided between fodder crops for livestock feeding and food crops (i.e. cereals). In Italy the favoured legume for farmers was alfalfa (i.e. *Medicago Sativa* L.) and in less percentage, clover (*Trifolium* sp.) in order to fix N into the soil, increasing yield production and to reduce the practice of fallow (Scarpa, 1963; Giardini, 2004; E. A. C. Costantini, 2013).

The use of the soil in Veneto region for the first half of the XIX century is described in Scarpa, 1963. The author divides land into agricultural areas and estimates the distribution of the different crops for each province is shown in Table 4.6 the percentage distribution... Following the book, between 70 and 90 % of the Veneto was covered by cropland, mostly mix cropping (e.g. cereals and vineyards - so called "*piantata*", or rotations of maize, oat, barley and sorghum)[34] and partially by simple cropping. Thanks to these agricultural systems, farmers were able to derive an income from the wine and wheat yields and to get food from the other crops. Another good practice in use of at that time was the grass strips left along vineyards to fulfil fodder requirements. Verona province counted already at that time the presence of rice fields, sometimes along with alfalfa. Mechanisation was linked to the use of plough or hoes by farmers. Fertilization was usually annual, but linked only to livestock cycle and not covering all the provinces. Grasslands were also partially intercropped with vineyard and the author confirms that the most popular grass legume was alfalfa and secondly clover. Cuts were made twice

[34] Coltura semplice e coltura promiscua

per year and soil was not tilled nor fertilized. Regarding irrigation only few fields in the low plain were declared "*adacquatori*" - irrigated. Two plagues threatened vineyards survival in Italy (and in the rest of Europe): meldew around 1850 and phylloxera in 1880–1890 decade. Because of this, in the successive decade's vineyard surface decreased considerably. Thanks to the diffusion of the American rootstocks, during the 1930s the viticulture regained surfaces and started to re-expand having its maximum of expansion in the 1950s - about 3,700 km^2. At the time of unification of Italy (i.e. 1861) some soils were drained and the watercourses organized.

Table 4.6 Distribution in % of the agricultural and forestry surface in Veneto Region (Scarpa, 1963).

	BL	PD	RO	TV	VE	VR	VI	TOT
cropland	8	**81**	65	63	46	63	47	46
grassland	**20**	10	10	17	12	7	10	14
pasture	**35**	1	9	10	9	6	12	14
forest	**23**	3	1	7	2	9	18	12
vineyards	-	1	-	-	-	**2**	1	1
productive fallow	14	1	3	2	6	8	12	9
marshes	-	3	12	1	**25**	5	-	4

In Table 4.7 shows the spin up sequence for the model for the two phases and for the block sequences that ranges between 1901 and 2100.

Table 4.7 Spin-up sequence simulated in each SCL unit.

	Equil. 1	**Equil. 2**	**Block sequences**
Time	1700 yrs	300 yrs	1901-2100
Land use	3 yr (W-O-F*) + pasture	4 yr (B-C-W-M**) + pasture	CLC and predicted land use
Fertilization	Organic	Organic	Organic and Mineral
Tillage intensity	Low	Low	Medium/Intense
Irrigation	No	No	yes

*W-O-F = low yield wheat – oat – fallow rotation typical of roman and middle-age agriculture

**B-C-W-M = low yield barley – clover – wheat – meadow rotation introduced in XVII – XVIII century

BLOCK sequences

The phase between 1901 and 2100 is divided into five specific blocks and reflects the three different changing CLC codes (e.g. 131_68_RVT3BSL1_**242_242_211**).

Block1

Between 1901 and 1970, the land use assumed for each SCL polygon reflects the CLC 1990, with some adjustments referring to low input intensity (i.e. low fertilization rates and low tillage), lower crop yields (i.e. maize (*Zea mais* L.) /wheat (*Triticum aestivum* L.) /sugar beet (*Beta vulgaris* L.) / silage) and higher presence of fodder crop (alfalfa) in the agricultural systems. Regarding the residue management, 50% of cereal straw (wheat) was assumed to be removed from fields.

This assumptions depend from the review done: at the beginning of 1900 many economical phenomena such as industrialization, emigration and drainage works influenced the agricultural sector (Scarpa, 1963). Following many historical books on agronomy and the data provided from *Catasto agrario*[35] by ISTAT, the drainages during 1920s in Basso Veronese, Polesine and Litoraneo Veneto, diminished considerably the percentage of marshes in favour of new arable land (e.g. in Venice province 50000 ha have been drainage between 1895 and 1915 and 36000 between 1915 and 1935). In the high and medium plain agricultural areas were characterised by a high concentration of mulberry orchards and vineyards, while the low plain was characterised by rice fields (code 213). Until the 1960s the agriculture has been conceived as traditional with vineyards and orchards in the family farms. Cropping systems included rotated meadow (often of legumes) and a fixed pattern of rotation which boosted the livestock sector. Following *Catasto agrario* wheat yield was 2 t ha^{-1} in 1920, grass 5.5 t ha^{-1} and annual alfalfa 5 t ha^{-1} in 1936-1939. In the cropping systems the sugar beet yield increased, from 14000 t ha^{-1} in 1910 to 30000 t ha^{-1} in 1929. Later on, after the second world war, the percentage of mixed cropping (mainly cereals) and grasslands started to diminish with respect to more simple cropping (e.g. cereals, fodder, sugar beet) typical of the extensive arable holdings. The traditional *Granturchino* (i.e. high concentration maize meadow) started to be replaced by silage maize, symbol of the big change of the forage systems (from pastures to annual alfalfa or clover grass) for the livestock sector (both meat and

[35] http://lipari.istat.it/SebinaOpac/.do?idDoc=0007129

milk cow). Following *Catasto agrario* maize yield was 2.7 t ha^{-1} in 1950 and 5 t ha^{-1} in 1969, wheat 4 t ha^{-1}, grass 8 t ha^{-1} and annual alfalfa 6.5 t ha^{-1} in 1968.

Block2

The period between 1971 and 1990 refers as well to CLC 1990 data and the cropping system is the same (6-year rotation maize/wheat/sugar beet/ silage maize/ alfalfa), but without the previous "low" management (e.g. soil ploughed to medium depth 30-35 cm (Giardini, 2004; Lugato & Berti, 2008)). This block is defined by higher inputs of in manure and fertilizers. In these years farmers abandoned traditional agriculture for a more dynamic and competitive one. Areas dedicated to meadow and livestock were reduced or suppresses with consequent loss of manure in favour of expanding cash crops (e.g. cereals, sugar beet). Maize yield was about 10 t ha^{-1}. Soil started to experience higher disturbance: farm mechanisation, chemical fertilisation (e.g. atrazine), herbicides, pesticides, etc (Scarpa, 1963; Tempesta, 2010; E. A. C. Costantini, 2013).

Block3

Between 1991 and 2000, refers to CLC 2000. Sugar beet cultivation has decreased in northern Italy due to the unfavourable market price evolution within EU and is replaced with soybean (*Glycine max* L. Merr.) with the following 6-year rotation maize/soybean/silage maize/wheat/silage maize/wheat (Lugato & Berti, 2008). As the areas dedicated to fodder almost disappear alfalfa has been removed from the cropping system. No fertilization has been applied to soybean crop.

Block4

Between 2001 and 2014, refers to CLC 2006 and is based on the current management.

The crop distribution and ratio in the cropping systems has been found through the statistics from the Farm Structures Survey 2010[36] from ISTAT (Veneto, 2011, 2013). Following this source more than half of the actual agricultural holdings in the Veneto are specialised in arable, together with that one's specialised in permanent crops they cover

[36]http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Agricultural_census_2010_-_provisional_results

the 80% of the total. About 33% of arable land is covered by corn, which the most extensively planted crop in Veneto. A 24% of the UAA is accounted for by forage crops, both these crops and corn provide fodder for the Veneto's animal husbandry industry. The rest of the UAA is divided between bread wheat (11%), soya (8%), grapes (9% equal to 70,000 ha[37]), horticultural crops (4%) and fruit growing (3%). Other minor crops: other cereals (e.g. barley, durum wheat, rice), other industrial crops (e.g. sugar beet, tobacco), energy crops (e.g. sunflowers and rape-seed). The fruit and vegetable sector include tuber crop, potatoes, Italian chicory, strawberries, peaches, nectarines cherries and kiwis. Regarding the energy crop sector in the Veneto 55 out of 85 biogas plants obtain their biomass from manure and specific crops, as well as food and agricultural waste and by-products. Regarding oil crops in 2008 the UAA for the production of biodiesel was equal to 6,560 ha. The Veneto has major potential in terms of the production and use of wood chip and firewood. At present, the region's forest, wood and energy system is not structured enough to meet the demand for fuel. Another major source of wood biomass is the Trees Outside of Forests (TOF) sector (i.e. hedgerows, farmland, riverbanks, floodplains, permanent cropland). It is estimated that Veneto produces an annual average of more than 26,000 t of fresh biomass with its *Short Rotation Forestry* (SRF)(Veneto, 2011).

The Veneto Region is a major user of fertilisers on account of its intensive farming. The Council Directive 91/676/EEC[38] of 12 December 1991 so called "*Nitrates directive*" concerning the protection of waters against pollution caused by nitrates from agricultural sources has been adopted at national level with the Dlgs. n° 152 of the 3rd of April 2006 and the DM of the 7th of April 2006.

The directive designated some vulnerable areas of land "*Nitrate Vulnerable Zones*" (ZVN in Italian) shown in Figure 4.16 and programmed local actions to regulate and limit the land application of mineral and organic fertilisers containing N, as well as livestock manure application.

---

[37] Source. Schedario Viticolo Veneto

[38] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31991L0676:EN:HTML

Table 4.4 Farm Structure Survey 2010: (a) Arable land category; (b) Cereals sub - category (ARPAV Veneto statistics[39]).

a	Arable lands							
province	Cereals	industrial crops	alternated Forage crops	horticultural crops	beetroot	Fallow land	potatoes	Legumes
VR	57.796,92	15.862,17	13.452,89	5.642,02	1.029,20	1.375,29	907,57	458,96
VI	35.881,47	5.101,73	9.333,65	1.107,93	389,34	512,46	299,77	42,16
BL	3.115,68	24,82	1.074,73	50,43	2,19	40,81	73,23	36,54
TV	51.112,43	13.363,18	11.302,51	1.244,79	184,41	2.229,45	104,8	40,99
VE	59.821,55	26.696,38	5.802,90	2.782,10	4.260,00	1.959,89	31,49	92,02
PD	87.313,57	12.229,08	10.639,37	2.595,73	3.962,64	1.968,26	297,75	77,28
RO	79.475,92	16.534,47	9.136,00	3.686,88	3.994,06	582,26	164,62	139,84
TOT	**374.517,54**	**89.811,83**	**60.742,05**	**17.109,88**	**13.821,84**	**8.668,42**	**1.879,23**	**887,79**

b	Cereals							
province	maize	Bread wheat & spelt	Durum wheat	barley	rice	Sorghum	oats	rye
VR	**34.047,73**	14.933,62	3.075,35	2.647,95	1.959,14	370,1	269,38	21,26
VI	**25.927,18**	6.202,92	2.163,39	1.031,97	143,37	168,25	137,75	42,41
BL	2.922,54	54,87	43,7	42,8	18,49	15,27	7,09	0
TV	**40.550,45**	6.905,19	1.224,51	1.760,87	5,27	191,88	216,74	20,45
VE	**41.619,81**	13.064,84	3.597,32	586,73	222,31	446,26	107,67	62,86
PD	**64.572,22**	17.049,36	3.651,11	1.062,15	106,37	340,02	281,64	107,27
RO	**46.138,90**	20.143,41	9.587,36	913	1.931,50	295,33	164,54	50,89
TOT	**255.778,83**	**78.354,21**	**23.342,74**	**8.045,47**	**4.386,45**	**1.827,11**	**1.184,81**	**305,14**

[39] http://statistica.regione.veneto.it/banche_dati_economia_agricoltura_db_2010.jsp

Veneto Region has adopted the legislation with the DGR n° 62 of the 17th of May 2006 and lately confirmed it with the DGR n° 243[40] of the 26th of February 2013. One of the most substantial measures included in the action programmes is the limitation of fertilizer application (i.e. mineral and organic) with a specified maximum amount of livestock manure to be applied, corresponding to 170 kg N ha^{-1} yr^{-1} in vulnerable zones, with a derogation from 24/1/2012 for the first four years of 250 kg N ha^{-1} yr^{-1}. At national level the limit for non vulnerable zones has been indicated as 340 kg N ha^{-1} yr^{-1}.

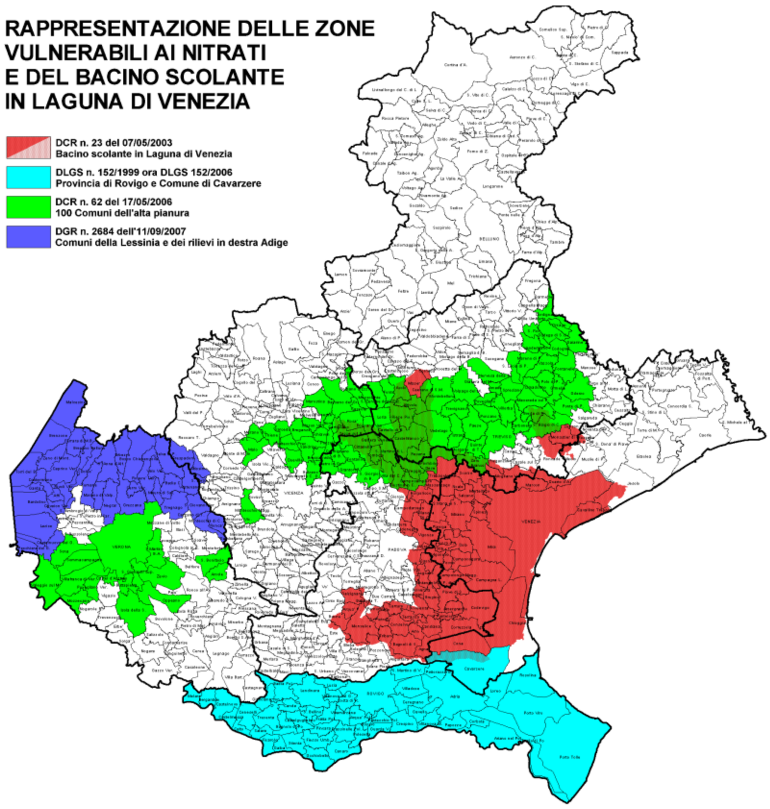


Figure 4.16 – In blue, light blue and green the ZVN areas in the Veneto Region (source: Veneto Region[41])

Since the adoption of the above legislation, there has been a move to reduce the use of fertilisers and phytopharmaceuticals: in 2009 the total use of agricultural fertilisers increased by +6.8%. But specifically mineral fertilisers decreased by -25.5%, organic fertilisers by -5.4%, organic-minero fertilisers by -23.8%, amendments increased by

[40] http://bur.regione.veneto.it/BurvServices/Pubblica/DettaglioDgr.aspx?id=246137
[41] http://www.regione.veneto.it/web/agricoltura-e-foreste/direttiva-nitrati

+76.8% and correctors decreased by -19.3% on the previous year. Amendments and correctors have a lower nutrient content, which means they can be used in higher doses, they increase and maintain the soil's fertility and SOM being environmentally friendly. The quality of the nutritional elements in fertilisers is evolving: the Veneto Region have reduced the surface area fertilised with phosphorous, nitrogen and potassium and increased the use of organic fertilisers allowed by organic farming. But still organic farming in the Veneto Region is not as developed as it is in the rest of Italy, equal to 15000 ha, 1.8% of entire UAA. One of the reasons is the intensive farming character of the systems (Veneto, 2011).

Table 4.5 Variation in % the main type of fertilisers used in the Veneto and in Italy referring to years 2008/09 (Source: Region Veneto- Istat).

	Mineral fertilisers	Organic fertilisers	Organo-mineral fertilisers	Amendments	Correctors	Total fertilisers
Veneto	-25,5	-5,4	-23,8	76,8	-19,3	6,8
Italy	-24,8	-21,0	-18,0	28,5	-0,3	-9,6

With regards to the mineral and organic N fertilization of the blocks and specifically Block4, the rates have been taken from studies and data coming from the UNIP-DAFNAE department (Morari *et al.*, 2010, 2012). The data sources are spatially distributed and calculated for municipality and not for LU. For this reason the parameters have been averaged with a matrix, weighting them in function of the surface occupied by a specific land use and the type of land use. The reference parameters used as fertilisers for different crops and land use (i.e. “*Dosi tecniche ottimali”*) are feasible for the Veneto plain. The data extracted refers to each SCL polygon and reflect the respecting changing of land use of the three CLC. No fertilization has been applied to soybean crop.

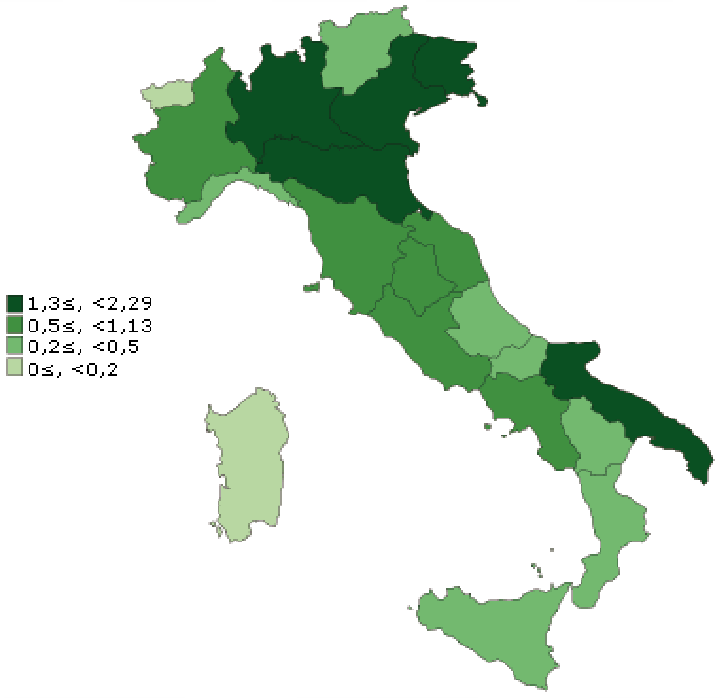


Figure 4.17 – Fertiliser (t ha^{-1} of UAA) distribution in agriculture per region of Italy – year 2009 (Source: Region Veneto- Istat)

Referring to tillage, the standard management used in the Veneto region is: conventional main tillage through mouldboard plough (MBP) close to the autumn and a secondary tillage more superficial, close to the planting date (E. A. C. Costantini, 2013, Giardini, 2004).

Regarding the residue management, 50% of cereal straw from wheat was assumed to be removed from crops (except for silage and grain maize).

Table 4.6 Example of the polygon 131_68_RVT3BSL1_242_242_211 (h refers to historical management and .f refer to future predicted management).

	Block 1	**Block 2**	**Block 3**	**Block 4**	**Block 5**
period	1901- 1970	1971- 1990	1991- 2000	2001 -2013	2014- 2100
CLC	CLC1990	CLC1990	CLC2000	CLC2006	CLC2006
management	242. h	242	242	211	211.f

Selected land management practices for SOC sequestration

Block5

This block ranges between 2014 and 2100, and is used to predict hypothetical management scenarios.

Following the assessment of chapter 3 a sub-set of the most promising management practices for C sequestration has been selected to be quantitatively assessed through scenario analysis using the CENTURY model.

The main criteria underling the selection of these measures is:

a) robust evidence in scientific literature of SOC accumulation as a result of the management practice;
b) the possibility to implement the specific management practice in the model routines;
c) the availability of data to describe the mitigation measure and possibility to integrate it within the simulation platform set-up (i.e. suitability to the regional agricultural context).

The effects on SOC levels due to the different alternative management practices (AMPs) scenarios are compared with a Business As Usual (BAU) scenario, representing the current management regime of Block4 repeated also in Block5.

The fertilization, crop residues and tillage management, if not clearly considered by the practice selected, refers to Block4, while period of application is dependent on the crop type.

BAU scenario

The BAU scenario evaluates the SOC dynamics in the long term period considering only the interaction with different climate change projections scenarios. The scenarios have been projected from 2014 to 2100, with breakdown periods in 2020, 2050, 2080 and 2100. The breakdown periods reflect short and long term policy decision processes at EU level (Lugato *et al.*, 2014a, 2014b).

Conversion from arable to grassland (AR_GR)

This land-use change scenario hypothesized the conversion of the currently arable land into grassland. The scenario could be perceived as not being feasible in an extensive sense because it involves the of the reduction of the area dedicated to arable marketable crops, but land degradation in Italy is increasing, especially in the Po plain (E. A. C. Costantini, 2013), for this reason it was decided to show the potential gain of SOM through the conversion degraded former arable land. For this scenario all the SCL polygons containing the 211, 241, 242 and 243 codes have been converted with the management of code 231. Simplified management conditions were implemented: the above ground biomass was removed to simulate three cutting events in May, July and September, while carbon restitution was implemented from manure application maintaining the actual rate of organic fertilization. No changes were made for animal livestock density (Lugato *et al.*, 2014b).

The opposite scenario of conversion of grassland (i.e. code 231) to arable land (GR_AR_LUC) has been simulated to show the potential severe loss in C pool.

Cropland management: COVER CROPS (CC)

This alternative scenario simulated the insertion of cover crops intercalated in the crop rotation, with total incorporation of the biomass into the soil before the successive main crop (e.g., green manure). The following two cover crop type categories were simulated: (a) mixed grass (i.e. gramionid + clover) following winter cereals; (b) rye grass preceding spring–summer crops (i.e. maize).

Cropland management: MINIMUN TILLAGE (MT)

A minimum tillage scenario was simulated with the substitution of the mouldboard plough with a more superficial tillage that is modelled by the higher distribution of litter in the surface SOC pools and by the reduction in decomposition coefficient controlling SOC turnover (Lugato *et al.*, 2014b).

Cropland management: CONSERVATION AGRICULTURE (CA)

This scenario simulates together minimum tillage with the cover crops and 50% crop residues removal.

Cropland management: NO IRRIGATION (NO_IR)

In this scenario no irrigation has been imagined due to climate changes and possible water scarcity.

Cropland management: CROP RESIDUES (RES)

In the BAU scenario, 50% of cereal straw is considered as being removed from the field (except for silage and grain maize in which above ground biomass and only grain were removed respectively). Two alternative scenarios were run considering: the incorporation of almost all cereal straw (5%).

Cropland management: FARMYARD MANURE FERTILIZATION (FYM)

This scenario simulates substitution of mineral fertilizer application with farmyard manure to evaluate the potential in OM accumulation.

Cropland management: AGROFORESTRY (AGF)

In this scenario rotation in the category arable land 211 has been partially converted into a medium term coppice poplar rotation with a 3-yr cutting cycle followed by winter wheat and grain maize.

Model validation

The modelling results simulated were compared with three independent SOC data sets

a) **ARPAV** – data referring to the period from 1990s to 2000s and representing past observations.

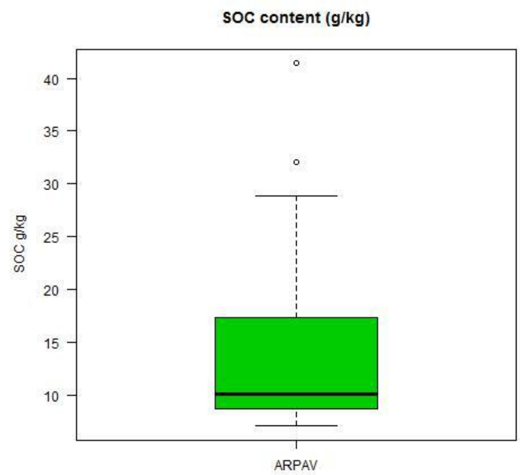


Figure 4.18 Boxplot of topsoil SOC content (g kg $^{-1}$) from the ARPAV points.

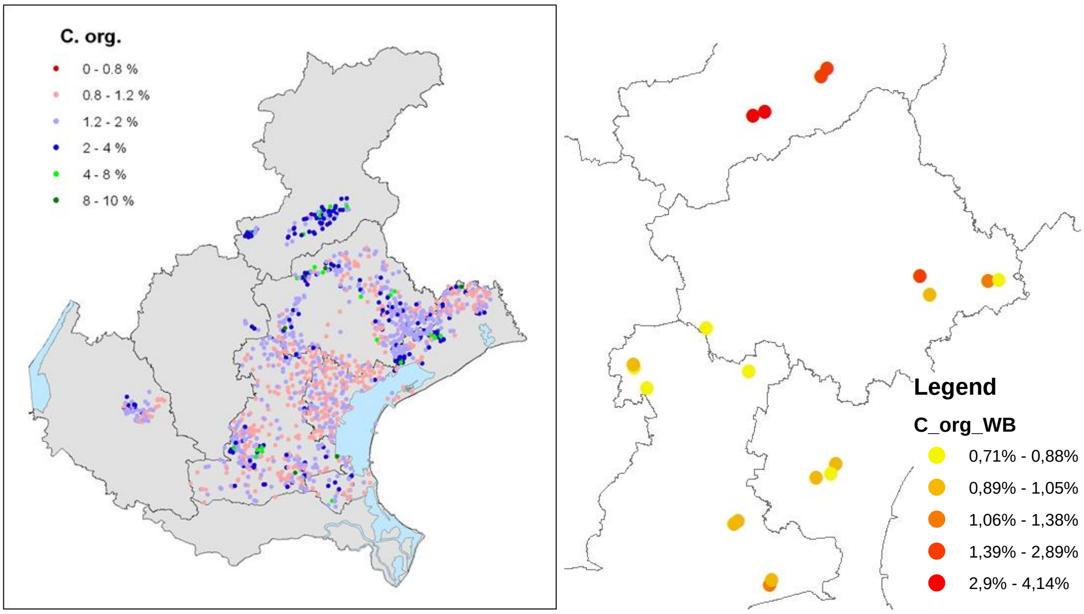


Figure 4.19 (left) ARPAV SOC points. (right) ARPAV SOC points taken into consideration for this study.

As regard to the data coming from ARPAV, it has been taken into consideration that the topsoil, SOC content was analysed with the Walkley Black technique (Walkley & Black, 1934) while BD was calculated through PTF.

b) **LUCAS2009**[42] (Land Use/Cover statistical Area Frame Survey) general topsoil survey.

The LUCAS project is a monitoring tool developed by DG EUROSTAT to follow the status of landscape diversity, to provide information on the harmonised land cover, land use and to monitor changes in management and coverage in the European Union. The LUCAS project (Land Use/Land Cover Area Frame statistical Survey) started in 2001 and is based on field observations of geo-referenced points. The survey is based on a regular 2 x 2 km grid defined as the intersection of around 1 million points covering the territory of the European Union (Martino & Fritz, 2008). Each point was classified into seven land cover classes using orthophotos or satellite images. From the stratified master sample, a sub-sample of 235000 points was extracted to be classified by field

[42] http://epp.eurostat.ec.europa.eu/portal/page/portal/lucas/methodology

observations in 2006 according to the full land use nomenclature. The focus of the survey was in agricultural land with a sampling rate of 50% for arable land and permanent crops, 40% for grassland and 10% for non-agricultural land. Direct field observations on 235.000 points gathering full information and data on land use/land cover and their changes over time in the EU-27 (Palmieri *et al.*, 2011). In 2009 the DG JRC has undertook for the first time a major soil collection programme across the EU under the LUCAS scheme. The points were selected as being representative of the EU land cover soils, stratified according to topography (i.e. the points above 1000 m in altitude were excluded with few exceptions) and all land uses/cover types, with higher weight for agricultural areas. The LUCAS 2009 soil survey is a topsoil (0-20 cm) subset survey of around 21,000 points (10% of the 235.000) sampled in 25 MS (EU-27 except Cyprus, Malta, Bulgaria and Romania) in Figure 4.20. Each soil sample was taken from the topsoil zone with a weight of ca. 0.5 kg and sent to a central ISO-certified laboratory for the analysis of physical, chemical and multispectral properties (i.e. particle size distribution, pH, OC, carbonates, NPK, CEC and visible and near infrared diffuse reflectance). In 2011 the methodology of LUCAS has been implemented for Bulgaria and Romania and around 2100 points have been surveyed in 2012. Malta and Cyprus collected the samples on a voluntary basis. In 2012-2013 also Iceland joined the scheme. The LUCAS 2009 soil survey represents the latest, most comprehensive and harmonized information on physic-chemical properties of topsoil from the EU (Tóth *et al.*, 2013; Ballabio *et al.*, 2014).

The samples were analysed for SOC expressed in g kg^{-1}. Only from the visualization of the points plotted in Figure 4.21 the levels of SOC highlight similar trends as the map of Jones *et al.*, 2005. Taking the main European climatic regions and land cover classes into consideration, SOC levels given by LUCAS database showed that woodland and shrub land have the highest level of SOC in all climatic regions, trend in line with the common understanding of high values of SOC in forest compared to other land cover classes. The lowest levels of SOC are observed in the Mediterranean climatic region, general trend confirming higher SOC content in northern regions respect to the southern parts of the continent.

In Panagos *et al.*, 2013b the LUCAS SOC data were compared with the OCTOP map from 2005 (Jones *et al.*, 2005a). The LUCAS SOC data were aggregated in 236 NUTS2 spatial units (i.e. European regional level, with 248 NUTS2 regions in 23 MS). Italy is divided into 21 NUTS2 regions and Veneto Region corresponds to the code ITD3.

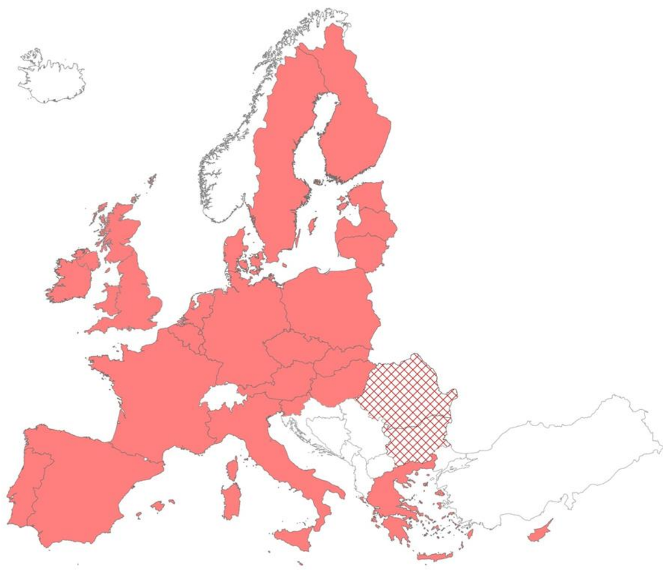


Figure 4.20 Map of the 25 MS where the LUCAS 2009 soil survey has been carried out (Bulgaria and Romania in squares because surveyed in 2012, Malta and Cyprus have no land use/cover data)

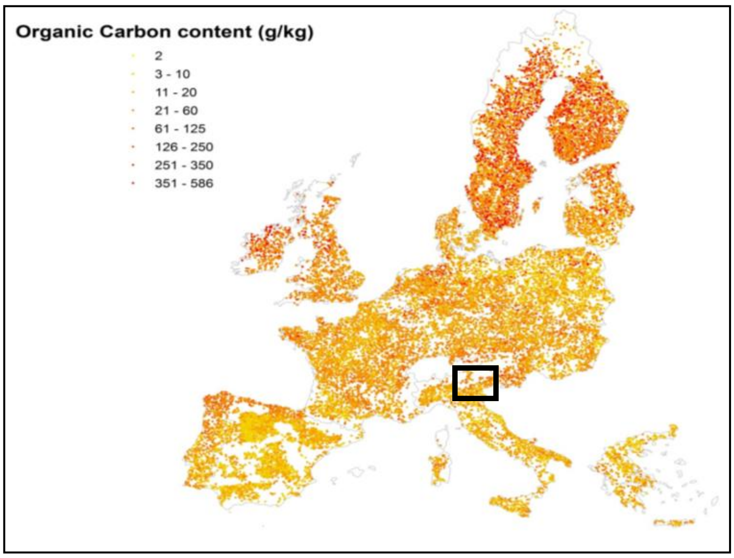


Figure 4.21 shows: (a) the distribution of around 19,515 points and their level of topsoil OC content (g kg $^{-1}$) in EU.

In the Veneto Region 88 points were delevered, with min of 6.70 g kg^{-1}, max 93.1 and mean 27.51 g kg^{-1}.

The SOC content in LUCAS points generally confirm the information coming from ARPAV source: the soils in the HighPplain (especially pastures) are the richest in SOC, with stocks higher than 75 t ha^{-1} due to higher litter accumulation, colder temperatures, higher concentrations in carbonates that inhibit OM mineralization and low management. In the Low Plain there are also some low lying areas, drained in the past, where the hydraulic conditions favoured an accumulation of the OM reaching sometimes very high levels (e.g. more than 100 t ha^{-1}). Generally the soils in the Medium and Low Plain are intensively managed and as result, they are characterised by low level of SOC content (e.g. less than 20 g kg^{-1}). Only temporary grasslands, vineyards and orchards have higher values. The provinces with lower SOC values are Rovigo, Venezia and Verona, coversely Belluno hosts the highest C pool.

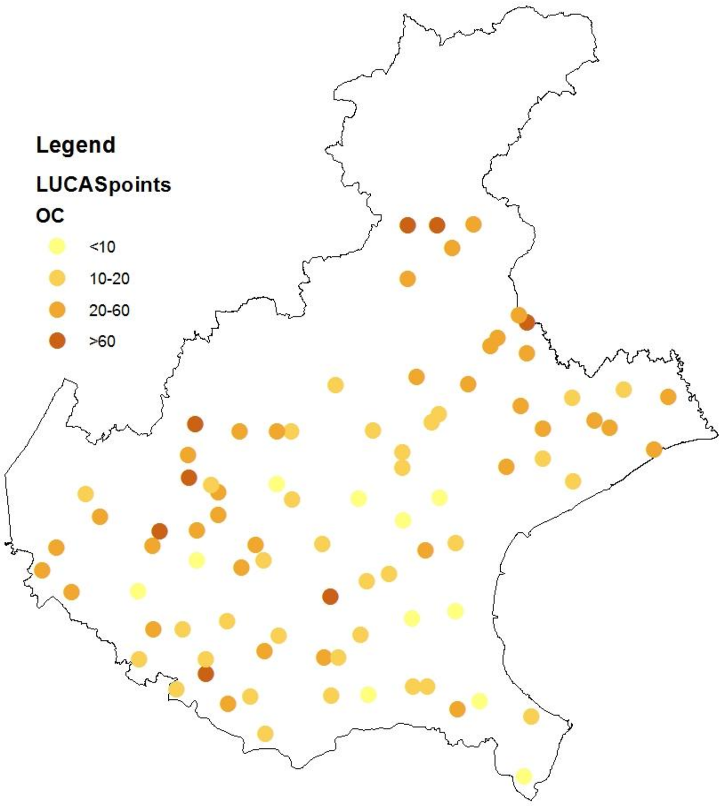


Figure 4.22 shows: (b) the distribution of the 88 LUCAS2009 in the Veneto Region points and their level of topsoil OC content (g kg^{-1}).

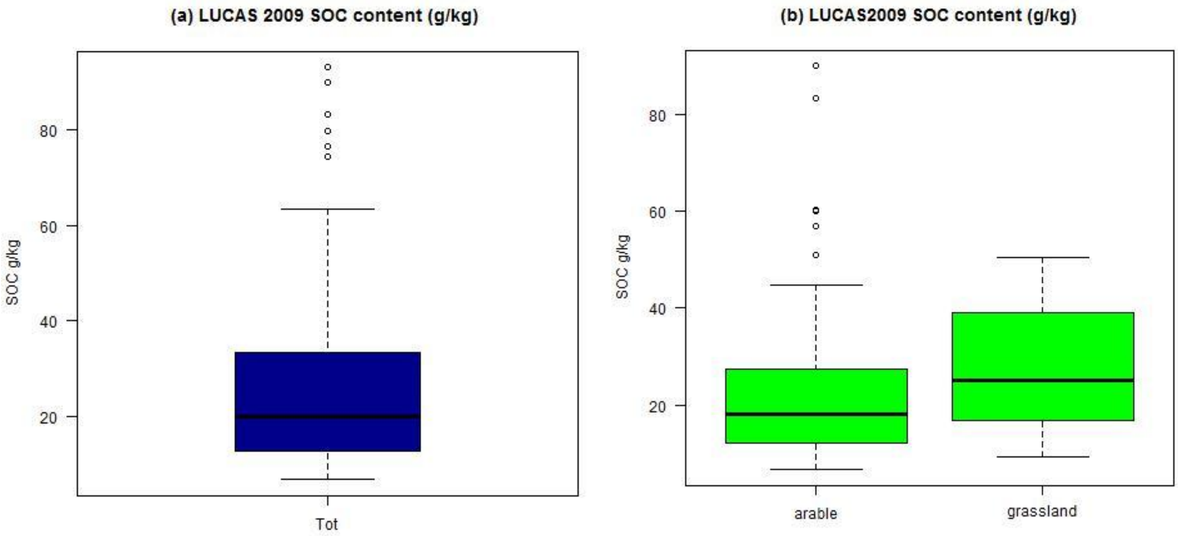


Figure 4.23 (a) Boxplot of SOC content (g kg $^{-1}$) the 88 LUCAS points; (b) Boxplots of SOC content (g kg $^{-1}$) divided for land uses.

c) **LUCAS2011** was a secondary survey done in 2011 on ARPAV point locations.

A limited soil survey campaign was carried out in Novemebr 2011 in the pilot area of Veneto Region applying the LUCAS 2009 methodology. This campaign was organized with the collaboration between three bodies: EC DG JRC, University of Studies of Padova – DAFNAE and ARPAV Veneto – Servizio Osservatorio Suolo. The scope was to apply the LUCAS 2009 topsoil survey methodology to an experimental soil survey of 40 samples collected across the region.

The selection of the survey points had been done previously on the basis of:

- 88 LUCAS soil samples surveyed in Veneto region in 2009 showed in figure 4.24.
- Soil samples data belonging to ARPAV, collected before 2000. ARPAV provided all the information related to the properties and the coordinates of the point.
- Climatic zones at regional scale
- Soil type
- Land Use (focusing on cropland and grassland).

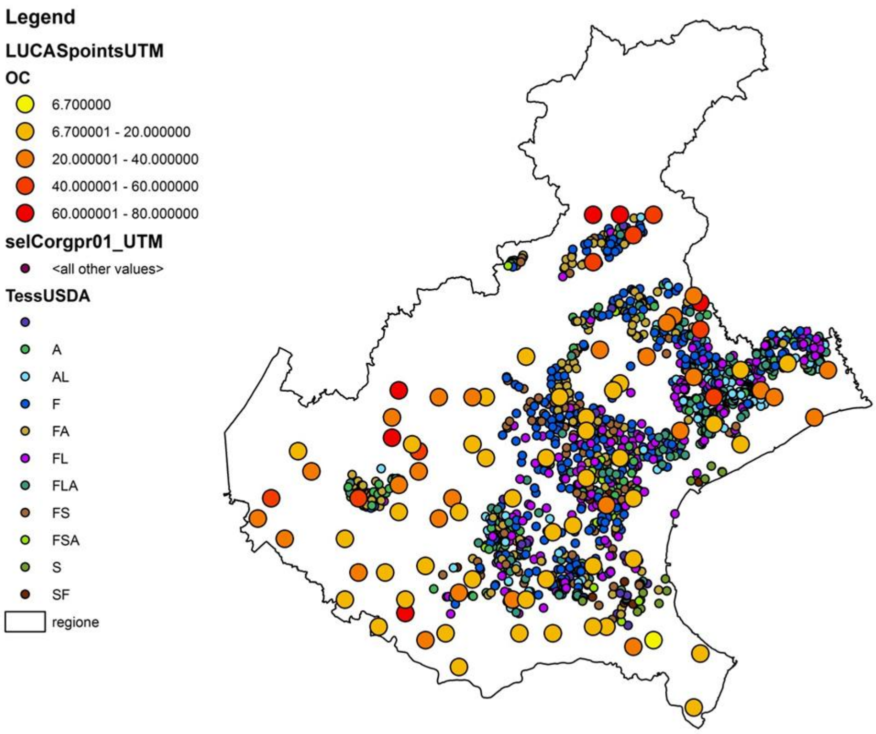


Figure 4.24 the LUCAS points following their correspondent OC content plus the ARPAV points classified following their texture.

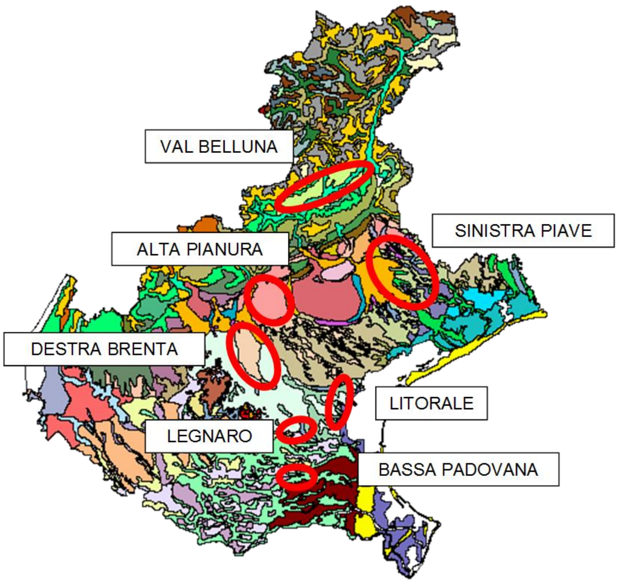


Figure 4.25 Soil map of the Veneto Region showing the areas surveyed in November 2011(ARPAV 2005).

The entire survey was realized following the steps described in the LUCAS methodology (reaching the point, filling the Land use/cover form, collecting the sample, taking the pictures). For each point the following procedure was followed:

- two disturbed samples of relatively topsoil 0-30 cm and 30-50 cm depth. Both the samples weighed approximately 0.5 kg and they are the result of the mixture of five subsamples. The first subsample was collected in the LUCAS point; the other 4 subsamples were collected at a distance of 2 m following the cardinal directions (N, E, S, W).
- Three undisturbed samples at different depths (5-10 cm, 10-15 cm, 35-40 cm) to measure BD.

After collection the 40 soil samples were dried and shipped to a laboratory in Hungary that carried out the analysis of LUCAS 2009. The laboratory carried out SOC analysis following the ISO method CHN.

The SOC content of the soil samples were successively re-analysed by the University of Studies of Padova – DAFNAE laboratories by the dichromate oxidation (Walkley & Black, 1934), the CNH and the CNH pre-treated with HCl. The 60 undisturbed samples were analysed to investigate the BD with the core method (Grossman & Reinsh, 2002) for later SOC stocks calculation in the topsoil layer.

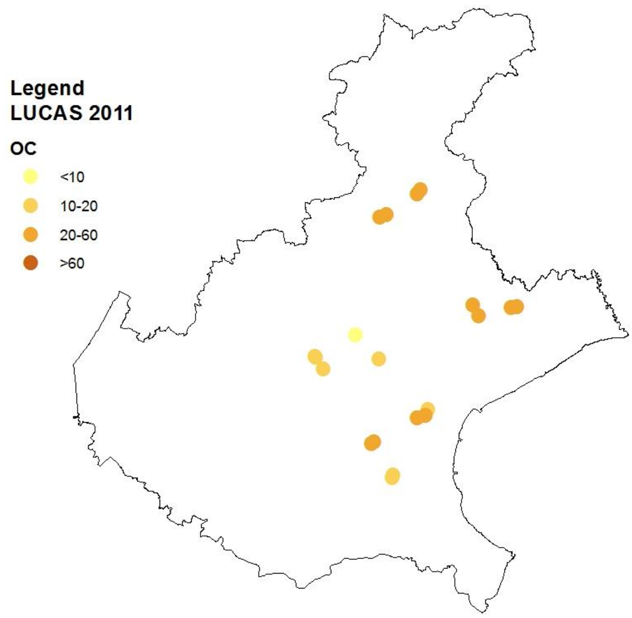


Figure 4.26 shows the distribution of the 20x2 depth- LUCAS 2011 points and their level of topsoil OC content following the CNS analysis (g kg $^{-1}$).

In figure 4.26 is shown the SOC content of the 20 points collected in 2011 for the topsoil layer from the CNS analysis. Higher content is shown from the points situated in the north (Val Belluna) and in the north-east (Sinistra Piave) reflecting the SOC ARPAV map and EIONET-SOIL SOC map discussed in chapter 2.

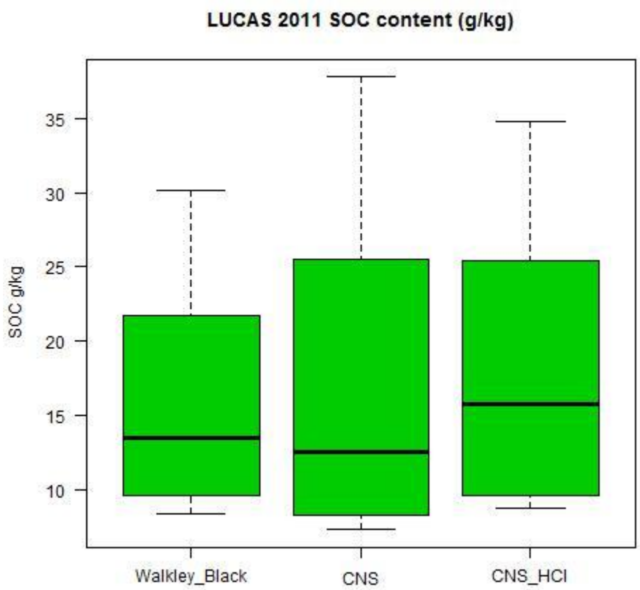


Figure 4.27 Box plots of LUCAS 2011 SOC content points in three different lab methodologies: Walkley Black (Walkley & Black, 1934), CNS analyzers, CNS analyzers with HCl pre-treatment (Schumaker, 2002)

Figure 4.27 shows the three laboratory methods adopted for the SOC content analysis, the average is similar for all the three methods, the Walkley Black results seem to have a slightly lower variability.

Results and Discussion

SOC sequestration potential

In this chapter, carbon sequestration is defined as the change in SOC stock related to human-induced activity such as the agricultural management[43]. SOC stocks in t ha^{-1} have been calculated for each dataset. The results have been compared with the model simulation values corresponding to the intersection of the SCL polygon with the point of the dataset, referring to the corresponding land use category (i.e. arable or grassland).

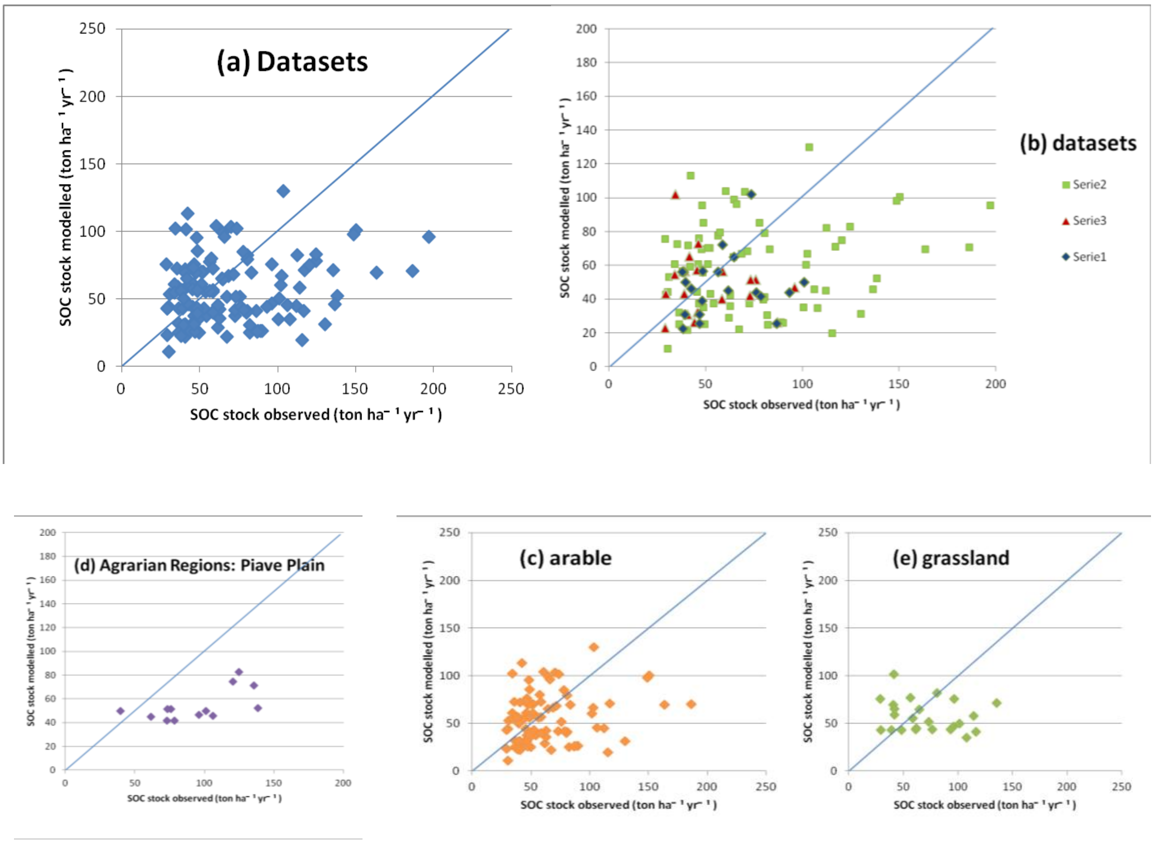


Figure 4.28a SOC model comparison against datasets inventory: (a) full inventory (LUCAS2009, LUCAS2011 and ARPAV.; (b) three datasets; (c) points in the arable land use;(d) points in the Piave Plain agrarian Region, in the green circle broadleaves; (e) points in the grassland land use.

[43] https://unfccc.int/methods/lulucf/items/4129.php

For the simulation presented in this chapter, the output from the model showed a good agreement with the three datasets measured values in all the

Aggregated land uses considered. It is important to note that the modelled data refer to the t C ha^{-1} for a SCL polygon and not to a single geo-referenced point.

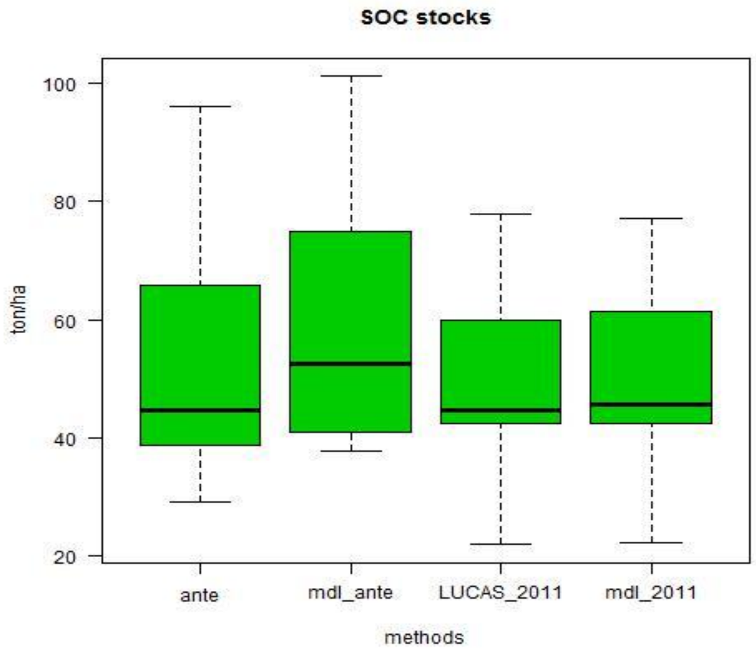


Figure 4.28b Box plots of SOC stocks (t ha^{-1}) from ARPAV points (ante); from the model simulated on the same years of ARPAV points (mdl_ante); from LUCAS 2011 points (LUCAS_2011); from the model simulated on the same years of LUCAS2011.

A comparison of the measured soil C stocks from past years (ARPAV source) and from the LUCAS2011 soil survey to the data modelled, in Figure 4.28 showed to follow similar averages and variations. Important to note that the data from the past are referring to a specific geo-referenced location and the data modelled are referring to the respective SCL polygon. SOC content is very much depending on climate, soil properties and land use but also on the level of disturbance of the exact point.

SOC stock in the BAU

The CENTURY model simulated the topsoil SOC stocks values for the Veneto Region in the period 2014-2100, after running through the spin-up, the map for the year 2010 is presented in Figure 4.29. It has been decided to show 2010 as current map to give the possibility to refer to the baseline map of EU produced for the CAPRESE project (Lugato *et al.*, 2014a).

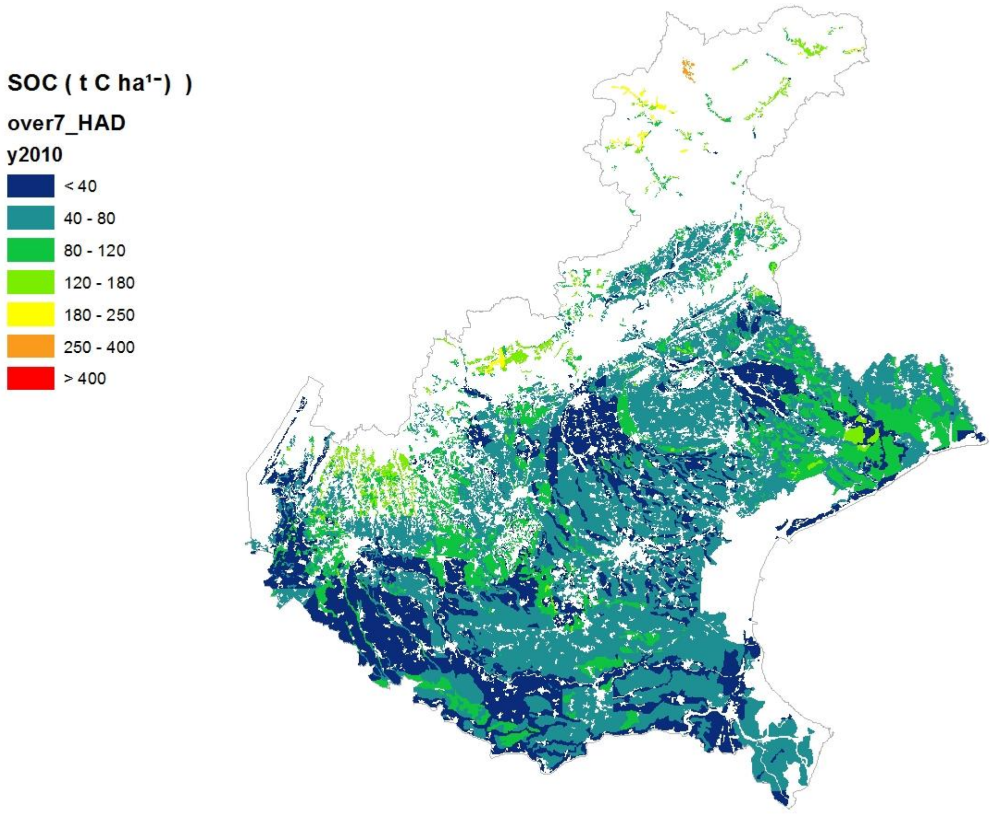
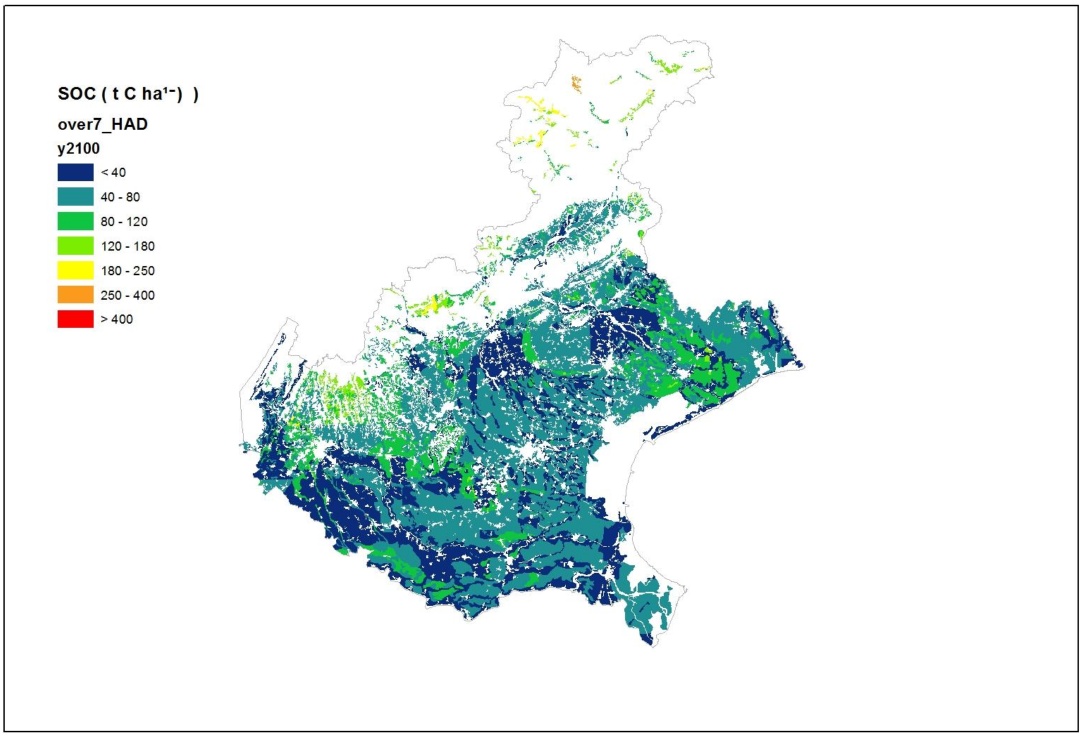


Figure 4.29 Simulated SOC stock (t ha^{-1}) in 2010 in the topsoil layer of Veneto agricultural soils.

The figure 4.29 shows the topsoil SOC pool in t ha^{-1} across Veneto Region in 2010, derived from the model CENTURY run through all the management sequences and agricultural land uses. The OC pool trends are similar to the trends of the previous ARPAV SOC stocks map and EIONET-SOIL OC content maps: very low levels (less than 40 or between 40 and 80 t ha^{-1}) for all the agricultural areas of the Low plain because of: the low mineralisation of OM due to intensive agricultural management, low organic fertilization amendments and farmyard manure; sandy or coarse soils. High pressure is due also to the increasing urbanization and sealing of large areas in the Low plain. The provinces with low stocks are Padova, Venezia, Treviso and Verona. In the province of Venice, close to the littoral, there are some hot-spots with higher OC due to the presence of peaty soils. Also in Lugato *et al.*, (2014a) the Mediterranean area showed the lowest SOC level in the EU, often below 40 t ha^{-1}. The majority of the agricultural land ranges between 40 to 80 or less than 40 t ha^{-1}. Interesting to note is that ARPAV recognizes as limit for good soil quality 1% for the OC content and 40 t ha^{-1} for OC stocks. Higher SOC pools, between 120 and 180 t ha^{-1}, corresponds to pastures in the Alps and to agricultural areas mixed with natural vegetations in the corresponding valleys (e.g. Val Belluna and Cadore). The interaction between pedo-climatic and agronomic conditions resulted in a complex SOC distribution in the areas of north-west Monti Lessini and north-east Val Belluna. The agricultural land predicted 61,79 Mt C (mean of 68,68 t C ha^{-1}, 63.99 for arable and 118.98 for grasslands) in 1043743 ha of total area.

Future predictions in SOC levels have been made using the current land use and management practices, with two very contrasting GCM-SRES scenarios. The aim was to establish the possible effects of climate change on a future SOC baseline, without considering any adaptation or mitigation strategies. The model simulated the SOC stocks across Veneto region, referring to the year 2100 for Had3_A1F1 more extreme and PCM_B1less extreme scenario. The simulated SOC stock (t ha^{-1}) maps in the topsoil layer of Veneto agricultural soils for the year 2100 in both climatic scenarios (Had3_A1F1 and PCM_B1) are visible in Figure 4.30. The difference between year 2000 and years 2020 and 2100 respectively are visible in Figure 4.31 and 4.32 in both climatic scenarios (Had3_A1F1 and PCM_B1).

For both climatic scenarios the CENTURY model predicted a decrease in 2020 in the total SOC stock. For the PCM_B1 less extreme scenario the stock changed from 62,01 Mt C of the year 2000 to 61,63 Mt C (- 0.38 Mt C) in 2020. The more divergent scenario Had3_A1F1 predicted a higher loss, 61,43 Mt C (- 0.57 Mt C). However the effect of the climatic scenarios started to diverge especially after 2050. In particular for PCM_B1 the SOC stock of the agricultural soils seems to accumulate C for a delta of 1.06 Mt C in 2100, while when CENTURY was driven by the Had3_A1F1 scenario, the stocks decrease of 3.24 Mt C by 2100. The rates of SOC loss for the BAU scenario ranges (2020, 2050,2080 and 2100) are visible in Table 4.7.



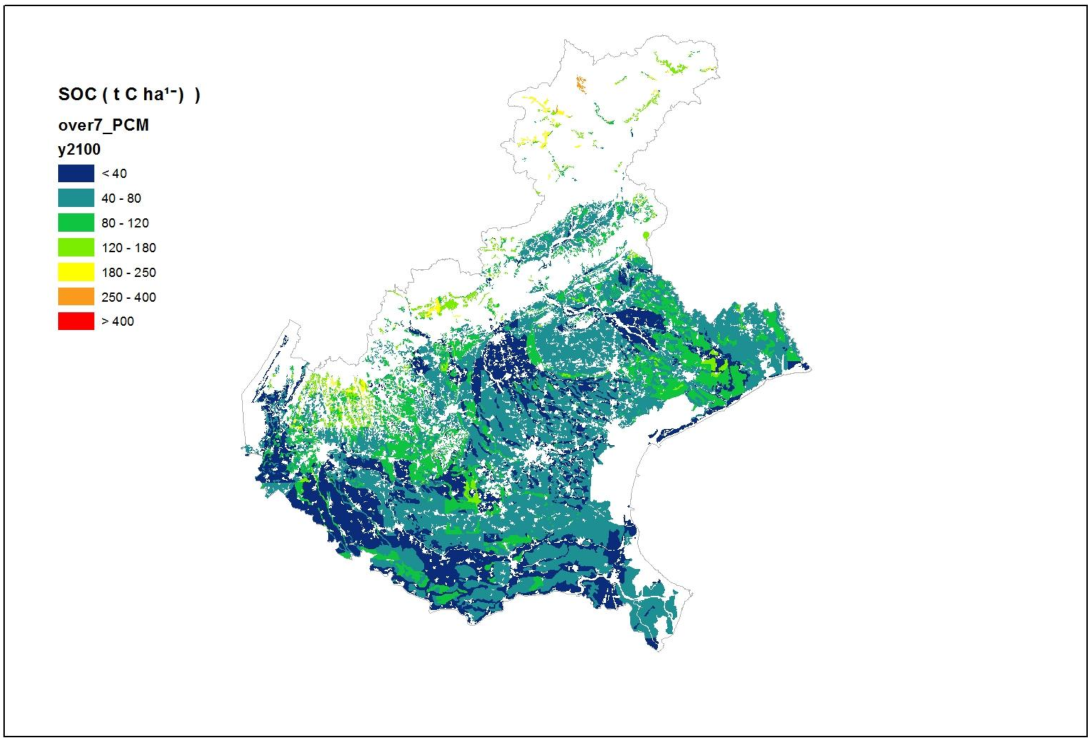


Figure 4.30 Simulated SOC stock (t ha^{-1}) in the topsoil layer of Veneto Region agricultural soils for the scenarios Had3_A1F1 and PCM_B1.

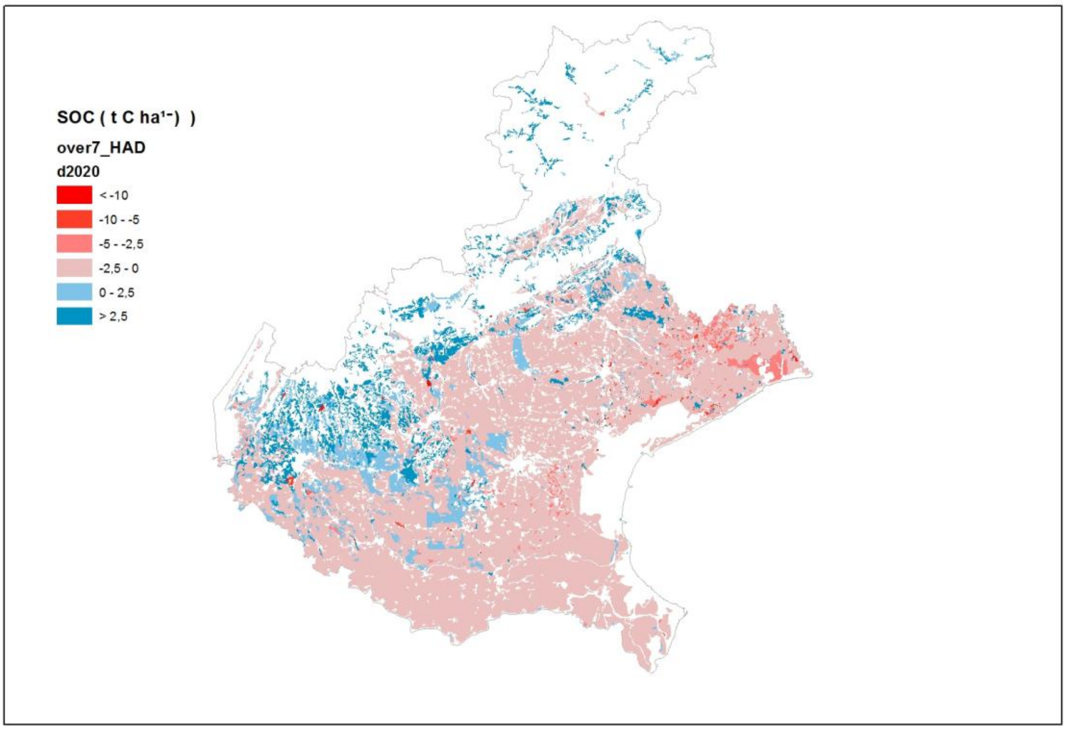
Table 4.7 Predicted SOC stock changes (Mt C) in the topsoil of Veneto region agricultural soils (area equal to 1043743 ha) in 2020, 2050, 2080 and 2100 for the BAU scenario.

	PCM_B1 (Mt C)	**HAD3_AIF1** (Mt C)
Δ2000-2020	-0.38	-0.57
Δ2000-2050	-0.15	-1 .07
Δ2000-2080	0.62	-1.91
Δ2000-2100	1.06	-3.24

In the figures 4.31 and 4.32 it's possible to identify the SOC changes (t ha^{-1}) on a regional basis. By 2020, short to medium term, the model predicted for the PCM_B1 scenario to gain in average 0.52 t ha^{-1} (0,026 t $ha^{-1}yr^{-1}$) and for the scenario HAD3_A1F1 a lower average of a 0.14 t ha^{-1} (0,007 t $ha^{-1}yr^{-1}$). Decreases can be seen clearly as red hotspots in the soils of the littoral plain of Venezia province, these areas have been drained in the past and are rich in limestone. Other areas of decreases correspond to the vineyards and the orchards in Treviso and Verona provinces.

In line with Lugato *et al.*, (2014a) on the Mediterranean countries, after 2050 the two scenarios started to diverge and the more extreme was characterized by a net loss of SOC. By 2100, long-term period, the model predicted for the PCM_B1 scenario to gain an average of 4,06 t ha^{-1} (0.040 t $ha^{-1}yr^{-1}$) and for the scenario HAD3_A1F1 a loss in average of -2,48 t ha^{-1}(-0.024 t $ha^{-1}yr^{-1}$) . Decreases can be seen clearly in red in the agricultural areas of the low-medium plain, characterised by alluvial deposit mainly limestone cambisols . The patchy effect of the two climatic grids can be seen in some areas of the Prealps.

The actual management in agricultural areas, represented by the BAU scenario, was on average a C source for both the scenario until 2050, (Table 4.7). After 2050 the BAU resulted to be a C sink for the PCM_B1 scenario, likely due to the higher C input in the projected period 2000-2100, as consequence of the higher productivity induced by the climate change. In the Had3_A1F1 scenario SOC depletion was estimated, due to the increasing SOC decomposition with the most warming temperatures.



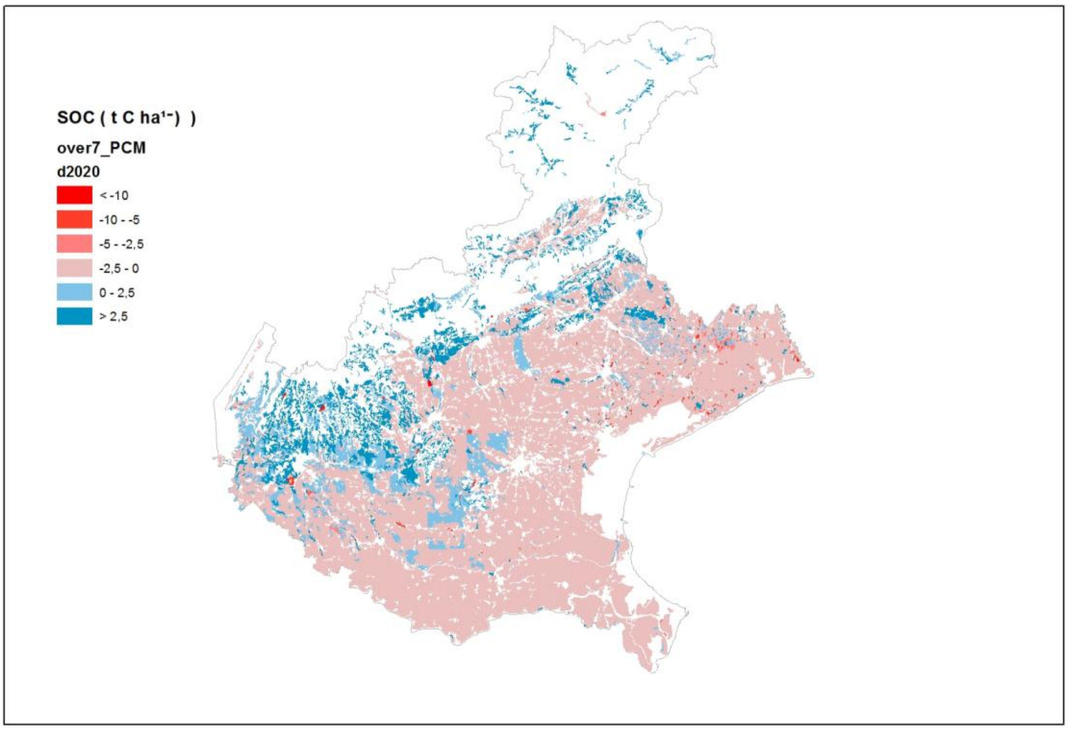
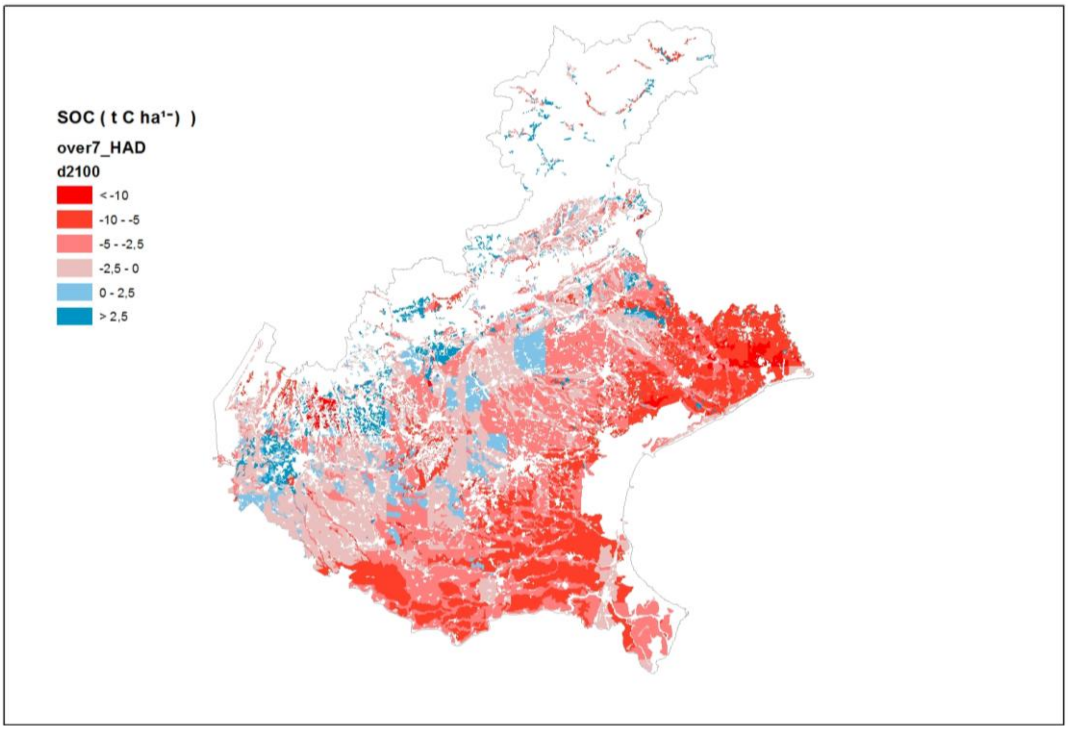


Figure 4.31 Predicted SOC stock change (t ha^{-1}) with respect to the year 2000 (referring to ARPAV datasets) in 2020 in the topsoil layer of Veneto Region agricultural soils for the scenarios Had3_A1F1 and PCM_B1.



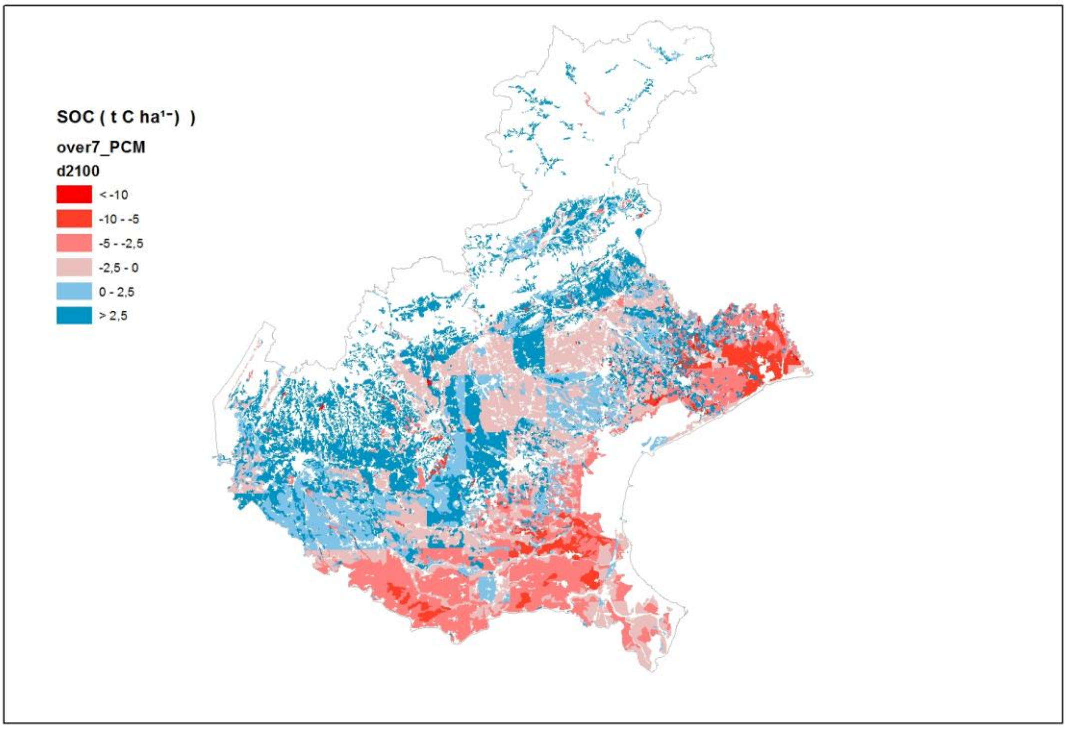


Figure 4.32 Predicted SOC stock change (t ha^{-1}) with respect to the year 2000 (referring to ARPAV datasets) in 2100 in the topsoil layer of Veneto Region agricultural soils for the scenarios Had3_A1F1 and PCM_B1.

SOC modelling at EU scale is still limited, especially for agricultural soils (Vleeshouwers *et al.*, 2002; (Morales *et al.*, 2007); Ciais *et al.*, 2010; Smith *et al.*, 2005b; Gervois *et al.*, 2008). At national and sub-national level there are more detailed studies on SOC stock and changes. A similar approach of this study is presented also in van Wesemael *et al.*, (2010b) for the major soil types and agricultural regions in Belgium, and in Álvaro-Fuentes *et al.*, (2011b, 2012) the model parameterization is detailed and accurate due to a better knowledge of the territory being studied and local agricultural practices.

For the same area, north-east of Italy, Morales *et al.*, (2007) estimated the change in net ecosystem exchange (NEE) for the Europe, using a LPJ ecosystem model. The results showed an average NEE of between 10 and 50 t C ha^{-1} yr^{-1} across different regional CMs and SRES scenarios in the period 2071–2100. In Smith *et al.*, (2005b), using C input from the LPJ and the SOC model RothC , predicted the general SOC depletion ranging from 0 to 2 t C ha^{-1} for the Had3_A2, in north-east Italy. The CESAR model application at European level of Vleeshouwers *et al.*, (2002) showed a net emission from arable soils in the period 2008–2012 of around 100 t C ha^{-1} yr^{-1} for the BAU. This value appears high, similar to an extreme land-use change and they estimated the possibility of sequestering C with FMY application and reduced tillage.

During the model spin up the partition of the of C pools is one of the factors affecting the accuracy of the model, especially if the aim of the simulation is to predict SOC stock in long-term. While the fast-intermediate turnover C pool could reach the equilibrium quite quickly, the passive pool has a turnover of hundreds to thousands of years, requiring a long spin up (Lugato *et al.*, 2014a). So far only LTEs limited studies tried to define management sequences starting from the natural vegetation and defining all the main land management and climatic changes, because of the large volume of information to be collected in order to reconstruct the past land use and land management (Gervois *et al.*, 2008; Vaccari *et al.*, 2012). This chapter tried to take a similar approach, but at regional level creating a spin up scenario based on 2000 years. This procedure tried to investigate and make later on some assumptions in order to be able to reconstruct all the exact land uses and managements for a long period.

SOC stock in the AMPs

AMPs were simulated from 2014 until 2100 and SOC stock changes were evaluated as a difference with respect to BAU projections at the same time frame (2020, 2050, 2080 and 2100), the data are summarized in table 4.8. The simulated AMPs trends showed different responses in relationship to the climate change scenarios. Each AMPs was run hypothesizing the full conversion of SCL arable land (1043743ha).

Table 4.8 Predicted SOC stock changes (Mt C) in the topsoil of Veneto region agricultural soils (area equal to 1043743 ha) in 2020, 2050, 2080 and 2100 for AMPs scenarios.

	ΔSOC							
AMPs	**2000-2020**		**2000-2050**		**2000-2080**		**2000-2100**	
	PCM_B1	**HAD3_AIF1**	**PCM_B1**	**HAD3_AIF1**	**PCM_B1**	**HAD3_AIF1**	**PCM_B1**	**HAD3_AIF1**
GR_AR	-0.99	-1.20	-1.75	-2.60	-1.11	-3.44	-0.68	-4.70
AR_GR	4.12	3.93	20.72	19.33	29.32	24.26	32.31	24.53
FYM	1.14	0.95	4.46	3.39	6.09	3.08	6.95	1.82
AGF	0.26	0.06	3.09	2.07	4.86	2.08	4.78	0.29
CC	0.45	0.22	2.29	1.14	3.64	0.64	4.20	-0.85
MT	0.65	0.47	2.76	1.78	3.64	0.81	3.86	-0.84
CA	1.59	1.37	6.09	4.81	7.78	4.33	8.04	2.48
NO_IR	-0.38	-0.59	-0.25	-1.18	0.58	-1.96	0.99	-3.25
RES5	0.41	0.19	2.02	0.97	3.46	0.59	3.90	-0.68

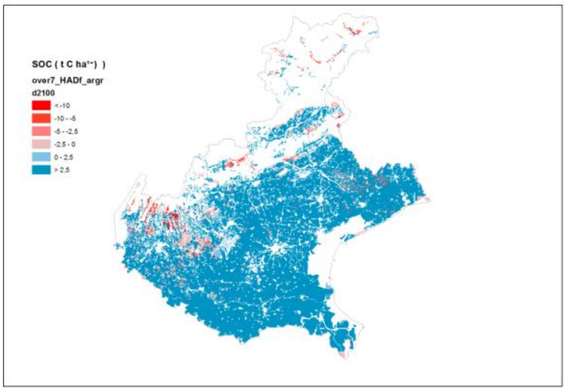
The following maps show the predicted SOC stock change (t ha^{-1}) for each AMPs referring to the time frame 2000-2100 in the topsoil layer of Veneto Region agricultural soils for both the scenarios Had3_A1F1 and PCM_B1.

Glossary:

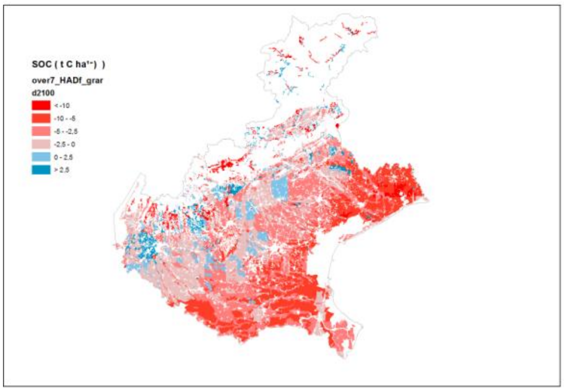
- AR_GR and GR_AR land conversion grassland/arable land
- AGF agroforestry
- CA conservation agriculture
- CC cover crops
- MTIL minimum tillage
- NO_IR no irrigation
- FMY farmyard manure
- RES5 residues removal 5%

Had3_A1F1

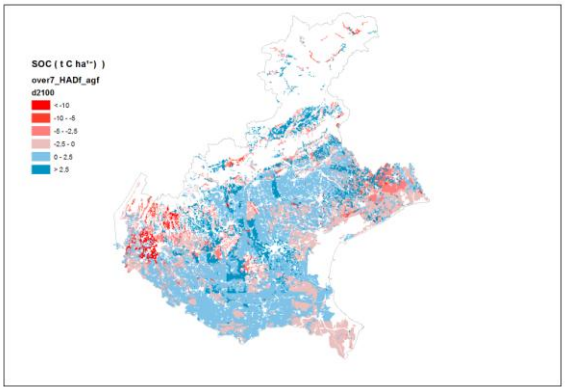
AR_GR



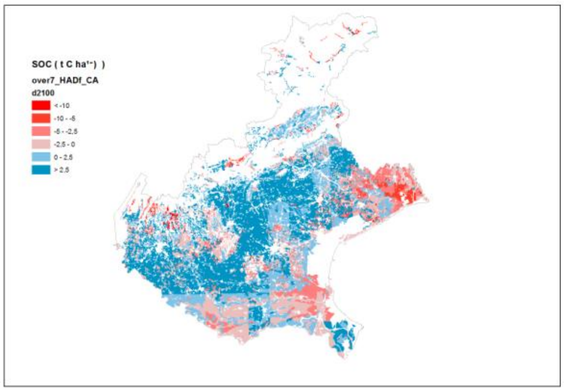
GR_AR



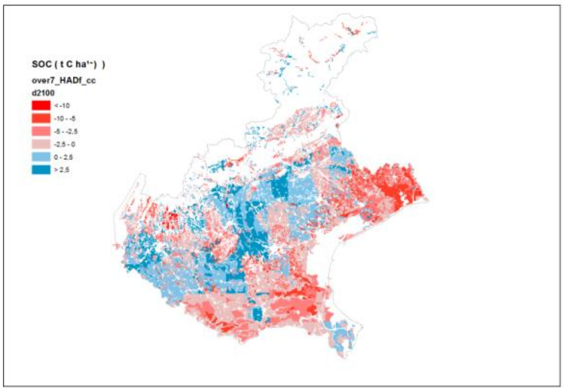
AGF



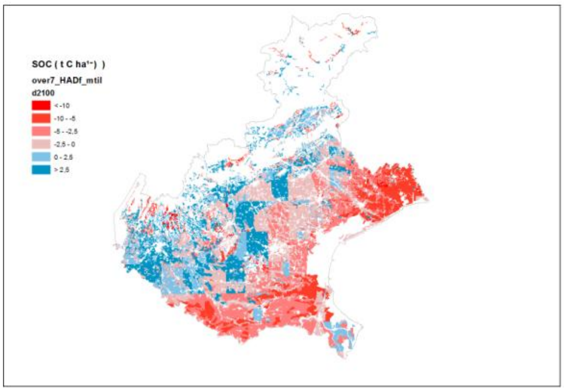
CA



CC

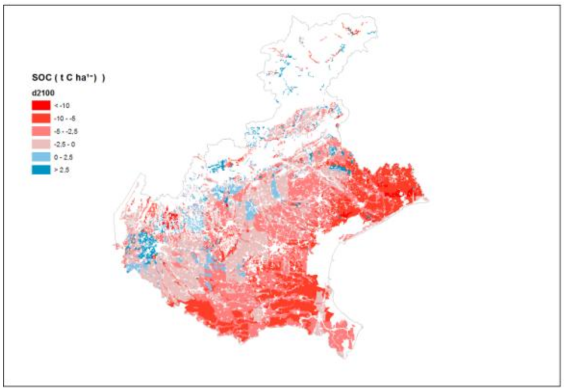


MTIL

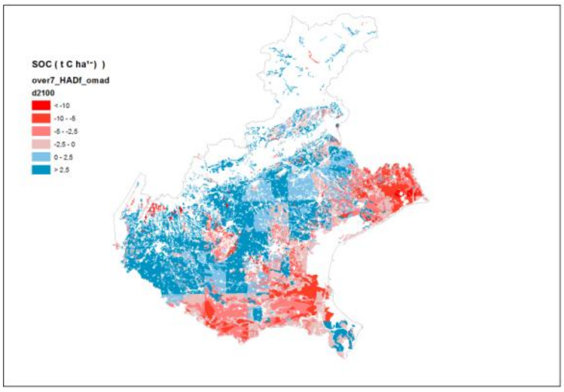


Had3_A1F1

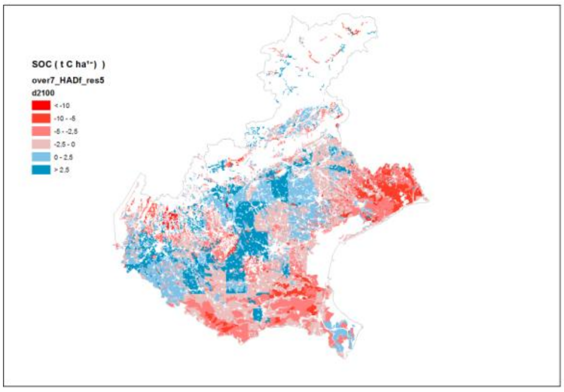
NO_IR



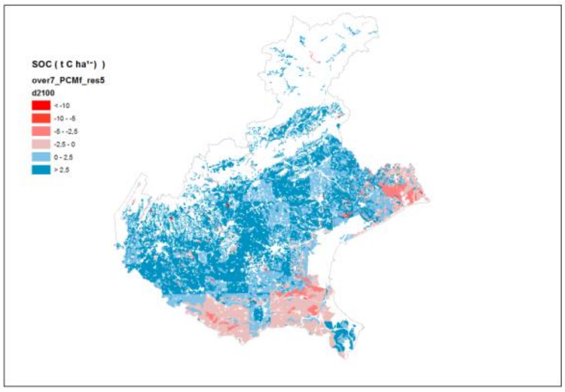
FMY



HAD3_A1F1 RES5

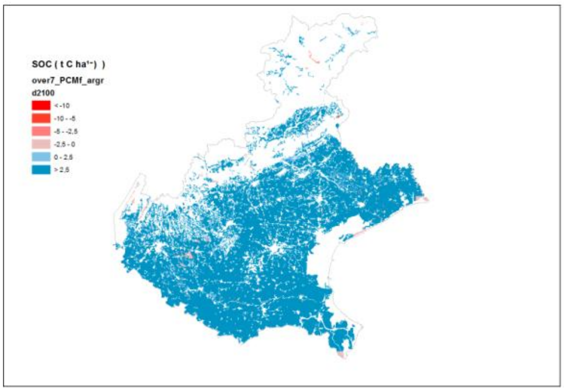


PCM_B1 RES5

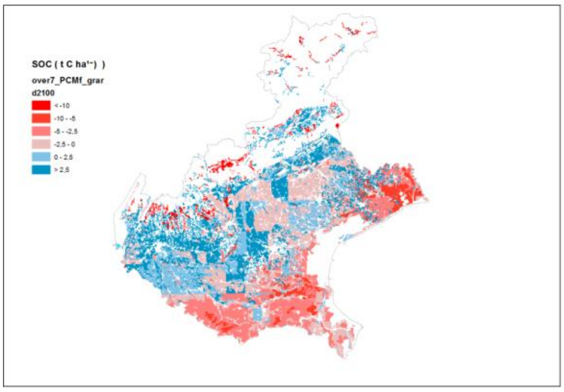


PCM_B1

AR_GR

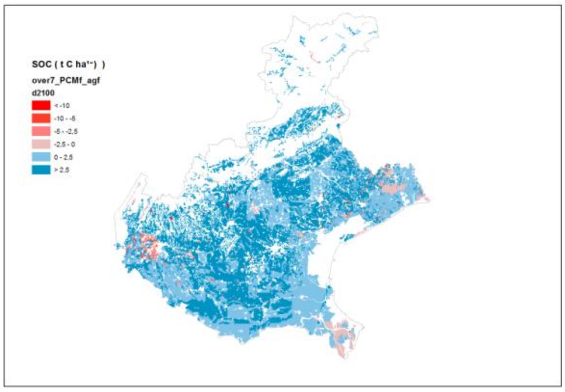


GR_AR

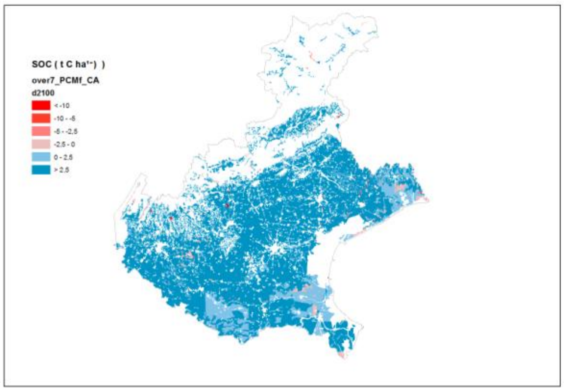


PCM_B1

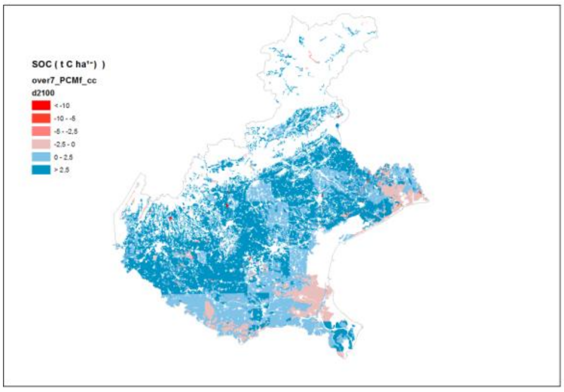
AGF



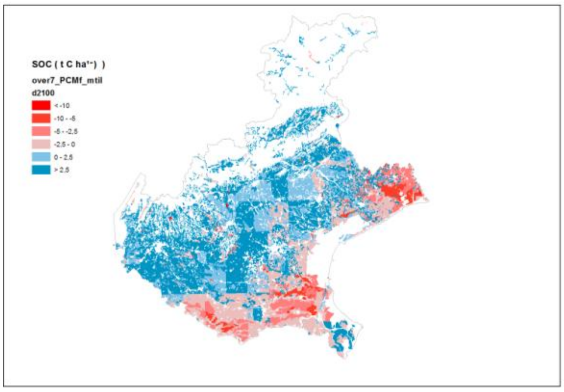
CA



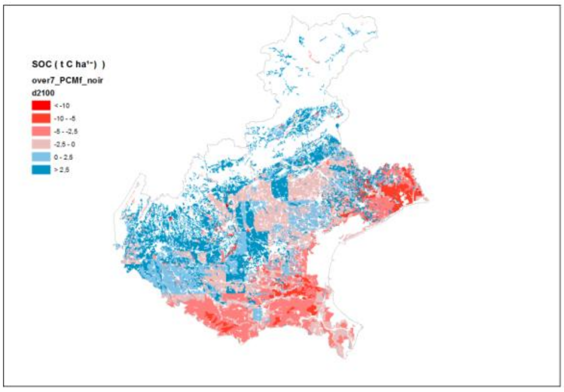
CC



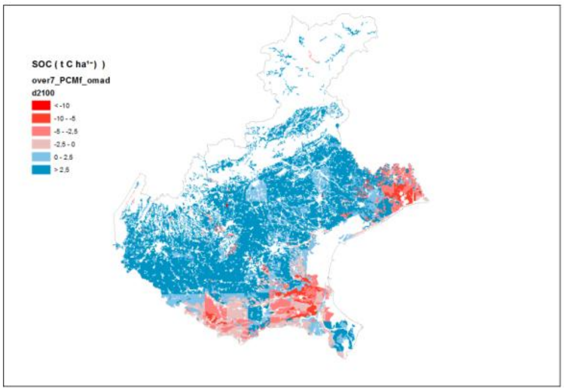
MTIL



NO_IR



FMY



Between all the AMPs scenarios simulated the conversion from arable to grassland (AR_GR) showed the highest technical carbon sequestration potential (Table 4.8). In both climatic scenarios the SOC stocks increased, especially from 2000 to 2050 the increase for PCM_B1 was about 20.72 Mt C and for HAD3_A1F1 19.33 Mt C. By 2100 the scenarios predicted about 32.31 Mt C for PCM_B1 and 24.53 for HAD3_A1F1. The median rates of C sequestration for the short-term range 2000-2020 were 4,07 t C ha^{-1} (0.203 t C ha^{-1} yr^{-1}) for PCM_B1 and 3.72 t C ha^{-1} (0,186 t C ha^{-1} yr^{-1}) for HAD3_A1F1. The same median rates didn't change much in the long- term (2100): for PCM_B1 25.36 t C ha^{-1} (0.25 t C ha^{-1} yr^{-1}) and 17.86 t C ha^{-1} (0.178 t C ha^{-1} yr^{-1}) for HAD3_A1F1. This management practice has not been selected to be implemented in the full UAA area of Veneto region, but the reasoning behind this selection is the increasing degradation of good quality land. A solution for all the land exploited in the past, actually degraded and not anymore productive would be the conversion to grassland.

On the other side, the negative conversion from grassland to arable (GR_AR) resulted in quick SOC losses until 2050 for both scenarios (-1.75 Mt C in 50 years for PCM_B1 and -2.60 Mt C for HAD3_A1F1) with average of -2.15 t C ha^{-1} (-0,043 t C ha^{-1} yr^{-1}) and -3,61 t C ha^{-1} for Had3_A1F1 (-0,072 t C ha^{-1} yr^{-1}). Thereafter in the long-term (by 2100) the PCM_B1 scenario seems to reach a stable situation, Had3_A1B1 instead has a slightly more negative rate of sequestration of -0,06 t C ha^{-1} yr^{-1}. This scenario has been modelled to show the importance of preserving permanent grasslands and potential SOC losses even converting a minimum percentage of grasslands, strongly offsetting the benefits of implementing another AMP.

The scenario related to the application of farmyard manure (FYM) showed positive accumulation in both climatic scenarios, by 2050 in the PCM_B1 the accumulation was of around 4.46 Mt C and for Had3_A1F1 of around 3.39 Mt C. After the PCM_B1 continue to accumulate with a positive trend instead the HAD3_A1F1 slowed the accumulation, the respective rate of SOC sequestration by 2100 are 0.10 and 0.029 t C ha^{-1} yr^{-1}. The results indicate that increasing the C input through FMY has the greatest effect in the short term. This selected management practice wanted to show the potential of applying organic inputs into the soil, even though further assessments should be done referring to the C/N ratio and the Nitrates Directive application in the referring local area. The application of FMY and the accumulation of SOC are linked to the soil types and precisely soil texture, referring to the map in the littoral sandy soils the accumulation appeared very low.

Referring to the agroforestry scenario (AGF) the variability in SOC changes was always positive. By 2100 the PCM_B1 scenario showed a gain of 4.78 Mt C with a rate of SOC sequestration of 0.075 t C ha^{-1} yr^{-1}, HAD3_A1F1 showed less positive values due to the extreme climatic change influence, 0.29 Mt C gained . The figures show the applicability of this selected practice for all the agricultural areas.

The simulation of cover crops presence (CC) within the rotation leads to a constant SOC accumulation for the PCM_B1 scenario and for Had3_A1F1 until 2050: 2.29 and 1.14 Mt C respectively. Also for this practice simulation the low plain sandy soils showed low accumulation rather than decreases in SO, while the rest of the agricultural areas showed a much higher variability related to the extreme climate change scenario. The cover crops were entirely incorporated, avoiding N leaching or losses typical of fallow. This effect was probably limited under the increasing drought conditions predicted by the Had3 scenario in which the water availability may be a limiting factor for plant growth.

The minimum tillage scenario (MTIL) for PCM_B1 increased of 0.65 Mt C in 2020, 2.76 Mt C in 2050 and 3.86 Mt C by 2100 and were uniformly distributed in all the plain except for the low limestone plain with sandy low lying soils where the map shows SOC losses. Had3_A1F1 scenario predicted gains until 2050 and losses in 2100.

The combination of minimum tillage and cover crops (CA) predicted to accumulate 6.09 Mt of C for PCM_B1 (0.11 t C ha^{-1} yr^{-1}) and 4.81 Mt C (0.082 t C ha^{-1} yr^{-1}) for HAD3_A1F1 by 2050. By 2100 for PCM_B1 SOC stock increased of 8.04 Mt C by a rate of 0.087 t C ha^{-1} yr^{-1} and of 2.48 Mt C for Had3_A1F1 with a very low rate of sequestration. After AR_GR this practice is the second one with the highest rates of SOC sequestration potential.

The selected practice of no irrigation showed negative trends for both scenarios (e.g. -0.59 Mt C by 2020 and -3.25 Mt C by 2100), except for PCM scenario by 2100, due to the climatic change influence and the no dependence to the practice of the land itself of no irrigation.

Referring to the residues straw incorporation scenario (RES5) the variability in SOC changes was small in the first time frames (2020 and 2050). By 2100 the PCM_B1 scenario showed a gain of 3.9 Mt C equal to a rate sequestration of 0.055 t C ha^{-1} yr^{-1}, HAD3_A1F1 showed negative values due to the extreme climatic change influence. The figures show for the PCM_B2 a quite widespread gain in all the agricultural areas where wheat is cultivated, for the HAD3_A1F1 the map shows a quite patchy situation depending on the climatic grid. The littoral in both scenarios show losses in SOC by 2100, while the north of the Region gained SOC showing the highest potential.

Referring to the meta-analysis at pan-EU level of chapter III the simulated SOC sequestration rates ranged almost between 0.1 – 1.0 t C ha^{-1} $yr^{-}1$. The meta analysis showed low measured C with some exception related to LTEs

Among the AMPs simulated, the conversion in land use from arable to grassland (AR_GR) was the most efficient in sequestering SOC. Many studies reported positive accumulation of 20 t C ha^{-1} in the 0–30 cm topsoil layer within 20 -40 years after the conversion. The opposite negative conversion(GR_AR) detected a loss of 40% of the SOC stock in less than 25 years in temperate zones (Conant *et al.*, 2001; Poeplau & Don, 2012; Poeplau *et al.*, 2011).

The residues management is one of the most feasible practices at farm level. In the paper of Powlson *et al.*, (2011b) the analysts of 25 LTE all over the world showed only small or no SOC changes. Also the simulated scenarios showed low potential (e.g. 0.055 t C ha^{-1} yr^{-1}). Although residue inputs have moderate impact on SOC stocks in long-term view other soil functions could greatly benefit from this application, as consequence a large exploitation of crop residues could have a strong impact on soil physical properties.

Both simulated and meta-analysis rates were similar. In Ogle *et al.,* (2005) meta-analysis the conversion from conventional to reduced tillage reported an increase of 1.09 - 0.03 over 20 years in temperate moist areas. In a modelling exercise of Bolinder *et al.,* (2010) the effects of more frequent tillage in a rotation increased SOC decomposition rate by about 20%. Other field experiments on the effect of minimum tillage on SOC changes and show positive effects with high uncertainty (Lal & Kimble, 1997; Baker *et al.*, 2007; Álvaro-Fuentes *et al.*, 2008, 2012b; Van den Putte *et al.*, 2010). The uncertainty is due to the biogeochemical impacts of tillage linked to soil physical conditions. The CENTURY model allows the partition of living and standing biomass into surface litter or soil pools but lack of the ability to parameterize the variation in the physical properties of soil empirically simulated by reducing the coefficient of decomposition of SOC pool (Lugato *et al.*, 2014b).

Studies on cover crop reported complex interactions between C, N and the rotations, some paper showed how the use of cover crops in Mediterranean areas could be less competitive due to climatic changes (Gomez *et al.*, 2011; Conceição *et al.*, 2013; Mutegi *et al.*, 2013).

As regard to agroforestry a recent paper of Lorenz & Lal, (2014) estimated that 50 years of agroforestry systems may sequester up to 2.2 Pg C above- and belowground. The simulated scenarios showed moderate positive SOC rates.

Conclusions

SOC models can downscale the knowledge achieved at EU scale as they mechanistically represent SOC dynamics in time, considering several feedbacks between climate, vegetation, carbon, soil type and anthropogenic intervention on homogenous pieces of land.

The platform described in this article attempts to create an harmonized and spatially detailed simulation of SOC in agricultural soils (arable and grassland).

The results suggest that, under current land management practices, the overall SOC stock for the Veneto Region is projected to generally decrease with regional differences.

There are numerous factors affecting the C balance of arable lands that makes difficult to model the C balance of these soils at regional scale. As there are so many factors, it is not easy to find meaningful research local studies to compare and cover the regional scale.

The Century model predicted an overall increase in C pool according to one climatic scenario and a decrease according to the other one by 2100. The data simulated showed a reflection in the observed.

This modelling exercise aimed to describe a tool able to delineate the areas where an AMP could be more effective, in order to help to design regional policies aiming to optimize SOC sequestration.

Human activity and management choices in agro-ecosystems could affect the C balance more strongly than climate change. SOC changes was more pronounced among the AMPs linked to climatic scenarios than among just different climate change scenarios.

Form the AMPs described great importance gained the C inputs provided by the grass component of the agro-ecosystem

The increase in C inputs into soil is considered an effective way to accumulate SOC, with a different efficiency in relation to the amount and the quality of C applied.

There is often a mismatch between C sequestration rates derived from LTEs and large-scale estimates produced by modelling simulations. When policy actions need to involve millions of hectares the LTE representativeness is uncertain.

This approach showed a different method to produce results of interest for policy making at EU and regional level, but more extrapolation to the country is needed.

However, biophysical results should be integrated into land use scenario and economic models, considering a range of market prices for C and the cost of AMP implementation, to eventually design the most cost-effective policy.

Veneto agricultural soils suited to agriculture are currently a source of C and with the adoption of selected mitigation techniques could be possible to control losses of C reported for the BAU scenario.

The actual trend in Veneto region for SOC is mainly linked to the loss of soil due to urbanization, confirming to be the main soil threat, and as second, is very much influence by the land use conversions and land management changes.

Acknowledgements

This chapter is largely based on the work done under the CAPRESE project[44] and the two papers linked (Lugato *et al.*, 2014b, 2014c)

[44] http://eusoils.jrc.ec.europa.eu/library/Themes/SOC/CAPRESE/ , http://mars.jrc.ec.europa.eu/mars/Projects/CAPRESE

References

Álvaro-Fuentes, J., Easter, M., Cantero-Martinez, C., & Paustian, K. (2011). Modelling soil organic carbon stocks and their changes in the northeast of Spain. *European Journal of Soil Science*, *62*(5), 685–695. doi:10.1111/j.1365-2389.2011.01390.x

Álvaro-Fuentes, J., Easter, M., & Paustian, K. (2012). Climate change effects on organic carbon storage in agricultural soils of northeastern Spain. *Agriculture, Ecosystems & Environment*, *155*, 87–94. doi:10.1016/j.agee.2012.04.001

Álvaro-Fuentes, J., López, M. V, Cantero-Martinez, C., & Arrúe, J. L. (2008). Tillage effects on soil organic carbon fractions in Mediterranean dryland agroecosystems. *Soil Science Society of America Journal*, *72*(2), 541–547. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-40849096308&partnerID=40&md5=04eca80c3663afaa7bdc5717fba9bad8

Álvaro-Fuentes, J., Morell, F. J., Plaza-Bonilla, D., Arrúe, J. L., & Cantero-Martínez, C. (2012). Modelling tillage and nitrogen fertilization effects on soil organic carbon dynamics. *Soil and Tillage Research*, *120*, 32–39. doi:10.1016/j.still.2012.01.009

Baker, J. M. M., Ochsner, T. E. E., Venterea, R. T. T., & Griffis, T. J. J. (2007). Tillage and soil carbon sequestration - what do we really know? *Agr Ecosyst Environ*, *118*(1-4), 1–5. doi:10.1016/j.agee.2006.05.014

Ballabio, C., Panagos, P., & Montanarella, L. (2014). Spatial prediction of soil properties at European scale using the LUCAS database as an harmonization layer. In *GlobalSoilMap: Basis of the Global Spatial Soil Information System - Proceedings of the 1st GlobalSoilMap Conference* (pp. 35–40). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84893706306&partnerID=40&md5=131b2d133f3b161cbc91b42929e9bd79

Batjes, N. H. (2011). Soil organic carbon stocks under native vegetation - Revised estimates for use with the simple assessment option of the Carbon Benefits Project system. *Agriculture, Ecosystems and Environment*, *142*(3-4), 365–373. doi:http://dx.doi.org/10.1016/j.agee.2011.06.007

Bolinder, M. A., Katterer, T., Andren, O., Ericson, L., Parent, L. E., & Kirchmann, H. (2010). Long-term soil organic carbon and nitrogen dynamics in forage-based crop rotations in Northern Sweden (63-64 degrees N). *Agr Ecosyst Environ*, *138*, 335–342.

Bortolon, E. S. O., Mielniczuk, J., Tornquist, C. G., Lopes, F., & Bergamaschi, H. (2011). Validation of the Century model to estimate the impact of agriculture on soil organic carbon in Southern Brazil. *Geoderma*, *167-168*, 156–166. doi:10.1016/j.geoderma.2011.08.008

Ciais, P., Wattenbach, M., Vuichard, N., Smith, P., Piao, S. L., Don, A., … Schulze, E. D. (2010). The European carbon balance. Part 2: Croplands. *Global Change Biology*, *16*, 1409–1428. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-77953111857&partnerID=40&md5=675a666f867c3fda6844f87bc2a644e2

Coleman, K., Jenkinson, D. S., Crocker, G. J., Grace, P. R., Klír, J., Körschens, M., … Richter, D. D. (1997). Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma*, *81*(1-2), 29–44. doi:10.1016/S0016-7061(97)00079-7

Conant, R. T., Paustian, K., & Elliott, E. T. (2001). Grassland management and conversion into grassland: Effects on soil carbon. *Ecological Applications*, *11*(2), 343–355.

Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0035065678&partnerID=40&md5=9bf736a6bef6f30fc7d9bdc32c3372f0
Conceição, P. C., Dieckow, J., & Bayer, C. (2013). Combined role of no-tillage and cropping systems in soil carbon stocks and stabilization. *Soil and Tillage Research, 129*, 40–47. doi:10.1016/j.still.2013.01.006
De Gryze, S., Lee, J., Ogle, S., Paustian, K., & Six, J. (2011). Assessing the potential for greenhouse gas mitigation in intensively managed annual cropping systems at the regional scale. *Agriculture, Ecosystems & Environment*, *144*(1), 150–158. doi:10.1016/j.agee.2011.05.023
E. A. C. Costantini, C. D. (Ed.). (2013). *THE SOILS OF ITALY*. *Land Degradation & Development* (Series Tit.). Springer Netherlands. doi:10.1007/978-94-007-5642-7
Eaton, J. M., McGoff, N. M., Byrne, K. A., Leahy, P., & Kiely, G. (2008). Land cover change and soil organic carbon stocks in the Republic of Ireland 1851-2000. *Climatic Change*, *91*(3-4), 317–334. doi:10.1007/s10584-008-9412-2
EC. (2006). (COM((2006)231 final) Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee of the Regions, Thematic Strategy for Soil Protection. (E. Commission, Ed.). Brussels: European Commission. Retrieved from http://ec.europa.eu/environment/soil/pdf/com_2006_0231_en.pdf
EC. (2009). *Final Report on the project Sustainable Agriculture and Soil Conservation (SoCo)* (p. 169). Office for Official Publications of the European Communities, Luxembourg: EC. Retrieved from http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/EUR23820.pdf
EC. (2011). (COM (2011)571 final) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Roadmap to a resource Efficient Europe. *Roadmap to a Resource Efficient Europe (COM(2011) 571 Final)*. Brussels: European Commission.
EC. (2012a). *(COM (2012) 93final). Proposal for a Decision of the European Parliament and of the Council on accounting rules and action plans on greenhouse gas emissions and removals resulting from activities related to land use, land use change and forestry* (Vol. 0042). Brussels.
EC. (2012b). *(COM(2012)46 final) Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, The implementation of the Soil Thematic Strategy and on going activities*. (E. Commission, Ed.) (Vol. 0086). Brussels: European Commission. Retrieved from http://www.parlament.gv.at/PAKT/EU/XXIV/EU/07/22/EU_72283/imfname_10018183.pdf
EC. (2012c). *COM. ((2012)94final) COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, Accounting for land use, land use change and forestry (LULUCF) in the Union's clim*. Brussels.
EC. (2012d). *COMMISSION STAFF WORKING DOCUMENT, Impact Assessment on the role of land use, land use change and forestry (LULUCF) in the EU's climate change commitments, Accompanying the document Proposal for a DECISION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on*. Brussels.

EC. (2014). Soil carbon sequestration for climate food security and ecosystem services - JRC Science ad Policy reports. EUR26540EN. In G. Halldorsson, F. Bampa, A. B. Porsteinsdottir, B. D. Sigurdsson, L. Montanarella, & A. Arnalds (Eds.), *Proceedings of the International conference 27-29 May 2013 Reykjavik Iceland* (p. 388). Brussels, Belgium: European Commission. doi:10.2788/17815

FAO. (2001). *Soil carbon sequestration for improved land management*. (R. M., Ed.) (World soil.). Rome: Fao.

FAO. (2004). *Assessing carbon stocks and modelling win-win scenarios of Carbon sequestration through land use changes*. (R. P. Hernandez, K. Parviz, & A. Jacques, Eds.)*Organization* (Vol. 1, pp. 1–156). Rome: Fao. Retrieved from http://books.google.com/books?hl=en&lr=&id=c5gS5HfBZQ4C&oi=fnd&pg=PA1&dq=Assessing+carbon+stocks+and+modelling+win-win+scenarios+of+carbon+sequestration+through+land-use+changes&ots=iX4h8Lr_yE&sig=akQE607KUcweRZ-EObxgyoKCSAQ

Gervois, S., Ciais, P., de Noblet-Ducoudré, N., Brisson, N., Vuichard, N., & Viovy, N. (2008). Carbon and water balance of European croplands throughout the 20th century. *Global Biogeochemical Cycles*, *22*(2), n/a–n/a. doi:10.1029/2007GB003018

Giardini, L. (2004). *Potenzialità produttiva e sostenibilità dei sistemi culturali*. P{à}tron. Retrieved from http://books.google.it/books?id=_edFAAAACAAJ

Gomez, J. a, Llewellyn, C., Basch, G., Sutton, P. B., Dyson, J. S., & Jones, C. a. (2011). The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. *Soil Use and Management*, *27*(December), 502–514. doi:10.1111/j.1475-2743.2011.00367.x

Grossman, R. B., & Reinsh, T. G. (2002). Bulk density and linear extensibility. In J. H. Dane & G. C. (Eds. . Topp (Eds.), *Methods of Soil Analysis, SSSA, Part 4 Physical Methods.* (pp. 201–227). Madison, WI: SSSA.

IPCC. (n.d.). LUCF SECTOR GOOD PRACTICE GUIDANCE. In *IPCC Good practice guidance for LULUCF*.

IPCC. (2000). *IPCC special report. Land use, land use change and forestry. Summary for Policy makers*. (I. R. N. Robert T. Watson Bert Bolin, N. H. Ravindranath, David J. Verardo, David J. Dokken, Ed.) (p. 375). Cambridge University Press, UK: IPCC.

IPCC. (2006). *IPCC (2006) Guidelines for National Greenhouse Gas Inventories, Institute for Global Environmental Strategies* . Cambridge University Press, Cambridge. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

IPCC. (2007). *Climate Change 2007: Synthesis report. Fourth Assessment report of the IPCC, AR4.* Cambridge University Press, Cambridge. Retrieved from http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

Janssens, I. A., Freibauer, A., Ciais, P., Smith, P., Nabuurs, G. J., Folberth, G., … Dolman, A. J. (2003). Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic CO_2 emissions. *Science*, *300*(5625), 1538–1542. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0038724260&partnerID=40&md5=a1f84c97f2ebb8bf7b1fed5c003f2ca1

Jenkinson, D. S., & Coleman, K. (2008). The turnover of organic carbon in subsoils. Part 2. Modelling carbon turnover, The turnover of organic carbon in subsoils. Part 2. Modelling carbon turnover. *European Journal of Soil Science*, *European Journal of Soil Science*, *59*, *59*(2, 2), 400, 400–413, 413. doi:10.1111/j.1365-2389.2008.01026.x

Jenkinson, D. S., & Rayner, J. H. (1977). The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Science*, *123*(5).

Jones, R. J. a., Hiederer, R., Rusco, E., & Montanarella, L. (2005). Estimating organic carbon in the soils of Europe for policy support. *European Journal of Soil Science*, *56*(5), 655–671. doi:10.1111/j.1365-2389.2005.00728.x

Kätterer, T., Andrén, O., & Persson, J. (2004). The impact of altered management on long-term agricultural soil carbon stocks – a Swedish case study, 179–187.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*(5677), 1623–1627. doi:10.1126/science.1097396

Lal, R., Griffin, M., Apt, J., Lave, L., & Morgan, M. G. (2004). Managing Soil Carbon. *Science*, *304*, 393. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-1942424129&partnerID=40&md5=2c31c5f4e5bc3194b094b7f4e5ffb72d

Lal, R., & Kimble, J. M. (1997). Conservation tillage for carbon sequestration. *Nutrient Cycling in Agroecosystems*, *49*(1-3), 243–253. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0000032908&partnerID=40&md5=77bab7a5fee0c0c8fbe5b1bb69d530ea

Lal, R., Kimble, J. M., Follett, R. F., & Stewart, B. A. (1997). *Soil Processes and the Carbon Cycle*. Taylor & Francis. Retrieved from http://books.google.it/books?id=1hrGaZvSHDIC

Lantz, A., Lal, R., & Kimble, J. (2001). Sustaining the Global Farm : Land Use Effects on Soil Carbon Pools in Two Major Land Resource Areas of Ohio, USA. In M. R. H. Stott D.E. Steinhardt G.C. (Ed.), *10th International Soil Conservation Organization Meeting* (pp. 499–502). Purdue University and the USDA-ARS National SoilErosion Research Laboratory.

Li, C., Frolking, S., Crocker, G. J., Grace, P. R., Klír, J., Körchens, M., & Poulton, P. R. (1997). Simulating trends in soil organic carbon in long-term experiments using the DNDC model. *Geoderma*, *81*(1-2), 45–60. doi:10.1016/S0016-7061(97)00080-3

Lorenz, K., & Lal, R. (2014). Soil organic carbon sequestration in agroforestry systems. A review. *Agronomy for Sustainable Development*, *34*(2), 443–454. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84899110089&partnerID=40&md5=ee18e66d7a2fa4ef40216a9a6350f853

Lugato, E., Bampa, F., Panagos, P., Montanarella, L., & Jones, A. (2014). Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. *Global Change Biology*, n/a–n/a. doi:10.1111/gcb.12551

Lugato, E., & Berti, a. (2008). Potential carbon sequestration in a cultivated soil under different climate change scenarios: A modelling approach for evaluating promising management practices in north-east Italy. *Agriculture, Ecosystems and Environment*, *128*(1-2), 97–103. doi:10.1016/j.agee.2008.05.005

Lugato, E., Panagos, P., Bampa, F., Jones, A., & Montanarella, L. (2014). A new baseline of organic carbon stock in European agricultural soils using a modelling approach. *Global Change Biology*, *20*(1), 313–26. doi:10.1111/gcb.12292

Lugato, E., Paustian, K., & Giardini, L. (2007). Modelling soil organic carbon dynamics in two long-term experiments of north-eastern Italy. *Agriculture, Ecosystems and Environment*, *120*(2-4), 423–432. doi:10.1016/j.agee.2006.11.006

Martino, L., & Fritz, M. (2008). New insight into land cover and land use in Europe. *Statistics in Focus*.

Milne, E., Paustian, K., Easter, M., Sessay, M., Al-Adamat, R., Batjes, N. H., … Adamat, R. A. (2007). The GEFSOC soil carbon modelling system: A tool for conducting regional-scale soil carbon inventories and assessing the impacts of land use change on soil carbon. *Agriculture, Ecosystems and Environment*, *122*, 125–136. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-34047265138&partnerID=40&md5=59228a04079e33f83b68bf8fde0539f7

Mitchell, T. D., Carter, T. D., Jones, P. D., Hulme, M., & New, M. (2004). A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). *Tyndall Centre Working Paper*, (Working Paper No. 55), 30.

Mondini, C., Coleman, K., & Whitmore, a. P. P. (2012). Spatially explicit modelling of changes in soil organic C in agricultural soils in Italy, 2001–2100: Potential for compost amendment. *Agriculture, Ecosystems & Environment*, *153*, 24–32. doi:10.1016/j.agee.2012.02.020

Morales, P., Hickler, T., Rowell, D. P., Smith, B., & Sykes, M. T. (2007). Changes in European ecosystem productivity and carbon balance driven by regional climate model output. *Global Change Biology*.

Morales, P., Sykes, M. T., Prentice, I. C., Smith, P., Smith, B., Bugmann, H., … Ogee, J. (2005). Comparing and evaluating process-based ecosystem model predictions of carbon and water fluxes in major European forest biomes. *Global Change Biology*, *11*(12), 2211–2233. doi:10.1111/j.1365-2486.2005.01036.x

Morari, F., Berti, A., Borin, M., Lugato, E., Cocco, E., & Polese, R. (2010). *MONITORAGGIO DELL'EFFICACIA DEI PROGRAMMI D'AZIONE NELLE AREE VULNERABILI DEL VENETO. MODULO 4-MONITORAGGIO AGROAMBIENTALE SECONDA FASE* (p. 151). Legnaro, Padova.

Morari, F., Lugato, E., Polese, R., Berti, A., & Giardini, L. (2012). Nitrate concentrations in groundwater under contrasting agricultural management practices in the low plains of Italy. *Agriculture, Ecosystems and Environment*, *147*(1), 47–56. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84655167981&partnerID=40&md5=94a3a17ba1bf7e29a663faa403e679c5

Mutegi, J. K., Petersen, B. M., & Munkholm, L. J. (2013). Carbon turnover and sequestration potential of fodder radish cover crop. *Soil Use and Management*, *29*(2), 191–198. doi:10.1111/sum.12038

Oelbermann, M., & Voroney, R. P. (2011). An evaluation of the century model to predict soil organic carbon: examples from Costa Rica and Canada. *Agroforestry Systems*, *82*(1), 37–50. doi:10.1007/s10457-010-9351-6

Ogle, S. M., Breidt, F. J., & Paustian, K. (2005). Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry*, *72*(1), 87–121. doi:10.1007/s10533-004-0360-2

Ogle, S. M., Swan, A., & Paustian, K. (2012). No-till management impacts on crop productivity, carbon input and soil carbon sequestration. *Agriculture, Ecosystems and Environment*, *149*, 37–49. doi:10.1016/j.agee.2011.12.010

Palmieri, A., Martino, L., Dominici, P., & Kasanko, M. (2011). Land cover and land use diversity indicators in LUCAS 2009 data. *Land Quality and Land Use Information in the European Union*.

Panagos, P., Ballabio, C., Yigini, Y., & Dunbar, M. B. (2013). Estimating the soil organic carbon content for European NUTS2 regions based on LUCAS data collection. *Science of The Total Environment*, *442*, 235–246. doi:10.1016/j.scitotenv.2012.10.017

Panagos, P., Hiederer, R., Van Liedekerke, M., & Bampa, F. (2013). Estimating soil organic carbon in Europe based on data collected through an European network. *Ecological Indicators*, *24*, 439–450. doi:10.1016/j.ecolind.2012.07.020

Parton, W. J. (1996). The CENTURY model. In D. Powlson, P. Smith, & J. Smith (Eds.), *Evaluation of Soil Organic Matter Models SE - 23* (Vol. 38, pp. 283–291). Springer Berlin Heidelberg. doi:10.1007/978-3-642-61094-3_23

Parton, W. J., Ojima, D. S., Cole, C. V, & Schimel, D. S. (1994). A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. *Quantitative Modeling of Soil Forming Processes. Proc. Symposium, Minneapolis, 1992*, 147–167. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0028571355&partnerID=40&md5=4695411a20a0ea2da8aeb318bd767f57

Parton, W. J., Stewart, J. W. B., & Cole, C. V. (1988). Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry*, *5*(1), 109–131. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-24344499030&partnerID=40&md5=25d2ce5d410a528eec0c1bdfaf8da8ee

Paustian, K., Brenner, J., Killian, K., Cipra, J., Williams, S., Elliott, E. T., … Bluhm, G. (2002). State-level analyses of C sequestration in agricultural soils. *Agricultural Practices and Policies for Carbon Sequestration in Soil*.

Paustian, K., Levine, E., Post, W. M., & Ryzhova, I. M. (1997). The use of models to integrate information and understanding of soil C at the regional scale. *Geoderma*, *79*(1-4), 227–260. doi:10.1016/S0016-7061(97)00043-8

Poeplau, C., & Don, A. (2012). Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe. *Geoderma*, *192*(1), 189–201. doi:10.1016/j.geoderma.2012.08.003

Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B. A. S., Schumacher, J., & Gensior, A. (2011). Temporal dynamics of soil organic carbon after land-use change in the temperate zone - carbon response functions as a model approach. *Global Change Biology*, *17*(7), 2415–2427. doi:10.1111/j.1365-2486.2011.02408.x

Powlson, D. S., Glendining, M. J., Coleman, K., & Whitmore, A. P. (2011). Implications for Soil Properties of Removing Cereal Straw: Results from Long-Term Studies. *Agronomy Journal*, *103*(1), 279. doi:10.2134/agronj2010.0146s

Rawls, W. J., Brakensiek, C. L., & Saxton, K. E. (1982). Estimation of soil water properties. *Transactions - American Society of Agricultural Engineers*, *25*(5), 1316–1320,1328. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0020430126&partnerID=40&md5=4221f308e8046a10a1721b98addd8d3c

Scarpa, G. (1963). *L'Agricoltura del Veneto nella prima metà del XIX sec: l'utilizzazione del suolo.* (p. 207). Industria libraria tipografica editrice. Retrieved from http://books.google.it/books?id=25dzQwAACAAJ

Schils, R. (2008). *Review of existing information on the interrelations between soil and climate change (CLIMSOIL) – Final Report. Contract number 70307/2007/486157/SER/B1:208.* (R. (ed) Schils, Ed.). Brussels: European Commission. Retrieved from http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/climsoil_report_dec_2008.pdf

Schumaker, B. A. (2002). *METHODS FOR THE DETERMINATION OF TOTAL ORGANIC CARBON (TOC) IN SOILS AND SEDIMENTS*. Las Vegas.

Shaffer, M. J., Liwang, M., & Hansen, S. (2001). *Modeling Carbon and Nitrogen Dynamics for Soil Management*. (XCR, Ed.). doi:10.1201/9781420032635.ch2

Smith, J. O., Smith, P., Wattenbach, M., Zaehle, Sön., Hiederer, R., Jones, R. J. A., … Smith J.a Smith, P. . W. M. . Z. S. . H. R. . J. R. J. A. . M. L. . R. M. D. A. . R. I. . E. F. . (2005). Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. *Global Change Biology*, *11*(12), 2141–2152. doi:10.1111/j.1365-2486.2005.001075.x

Smith, J., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R. J. A., … Ewert, F. (2005). Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. *Global Change Biology*, *11*, 2141–2152. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-33644548604&partnerID=40&md5=0f4af4a3d3a9e1bcec1a832855d31770

Smith, P. (2004). How long before a change in soil organic carbon can be detected? *Global Change Biology*, *10*(11), 1878–1883. doi:10.1111/j.1365-2486.2004.00854.x

Smith, P., & Falloon, P. (2005). Carbon sequestration in European croplands. *SEB Experimental Biology Series*, 47–55. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-34748821200&partnerID=40&md5=7d88c5626383c8b87ef83768d44c9346

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., … Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 789–813. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-40949120517&partnerID=40&md5=67f5dcd5ae9ef346f2a330cdf2b81294

Smith, P., Powlson, D. S., Smith, J. U., (Ted) Elliott, E. T., & Editors, G. (1997). Preface. *Geoderma*, *81*(1-2), 1–3. doi:10.1016/S0016-7061(97)88180-3

Smith, P., Smith, J. U., Powlson, D. S., McGill, W. B., Arah, J. R. M., Chertov, O. G., … Whitmore, A. P. (1997). A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. *Geoderma*, *81*, 153–225. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0031439311&partnerID=40&md5=e5e01954706b48110c580a9efc0a2a9e

Tempesta, T. (2010). The perception of agrarian historical landscapes: A study of the Veneto plain in Italy. *Landscape and Urban Planning*, *97*(4), 258–272. doi:http://dx.doi.org/10.1016/j.landurbplan.2010.06.010

Tóth, G., Jones, A., & Montanarella, L. (2013). *LUCAS Topsoil Survey methodology , data and results* (EU.). Luxembourg. doi:10.2788/97922

UN. (1997). KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE. Retrieved from http://www.unfccc.int

Vaccari, F. P. P., Lugato, E., Gioli, B., D'Acqui, L., Genesio, L., Toscano, P., … Miglietta, F. (2012). Land use change and soil organic carbon dynamics in Mediterranean agro-ecosystems: The case study of Pianosa Island. *Geoderma*, *175-176*, 29–36. doi:10.1016/j.geoderma.2012.01.021

Van den Putte, A., Govers, G., Diels, J., Gillijns, K., & Demuzere, M. (2010). Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture. *European Journal of Agronomy*, *33*(3), 231–241. doi:10.1016/j.eja.2010.05.008

Van Wesemael, B., Paustian, K., Meersmans, J., Goidts, E., Barancikova, G., & Easter, M. (2010). Agricultural management explains historic changes in regional soil carbon stocks. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(33), 14926–14930. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-77957061505&partnerID=40&md5=9da035eb02b2b130c6e645eb67ea0208

Veneto, R. (2011). *Rapporto Statistico 2011*. Retrieved from http://statistica.regione.veneto.it/ENG/Pubblicazioni/RapportoStatistico2011/index.html

Veneto, R. (2013). *Rapporto statistico 2013. Trasformazione*. Retrieved from http://statistica.regione.veneto.it/ENG/Pubblicazioni/RapportoStatistico2013/index.html

Vleeshouwers, L. M., Verhagen, A., & Verghagen, A. (2002). Carbon emission and sequestration by agricultural land use: a model study for Europe. *Global Change Biology*, *8*(6), 519–530. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0036295548&partnerID=40&md5=135ecdd0af7d7fcb83f26ac93d2955cb

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science*, (37), 29–38.

Wang, D., Hejazi, M., Cai, X., & Valocchi, A. J. (2011). Climate change impact on meteorological, agricultural, and hydrological drought in central Illinois. *Water Resources Research*, *47*(9), n/a–n/a. doi:10.1029/2010WR009845

Wattenbach, M., Sus, O., Vuichard, N., Lehuger, S., Gottschalk, P., Li, L., … Smith, P. (2010). The carbon balance of European croplands: A cross-site comparison of simulation models. *Agriculture, Ecosystems and Environment*, *139*, 419–453. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-78449248932&partnerID=40&md5=8b7a4760480b86b7f57e95b948745777

Chapter V

General conclusions

Conclusions

The databases available at EU level but also at regional level showed high variability due to different monitoring protocols, lab methods, application of different land use masks and PTRs.

In general the potential SOC sequestration of the selected promising mitigation options range from between 0.2 to 1 Mg C ha^{-1} yr^{-1}. The highest potential with conservation of organic soils and adoption of agroforestry techniques.

The accurate estimation and prediction of SOC in agricultural soils is strongly related to the specific characteristics of agro-ecosystems. The SOC balance is often mainly driven by anthropogenic actions rather than by climate change. For this reason there is no single optimum option that, if applied across the EU or even across the Veneto Region, could give an absolute certain rate of SOC sequestration. Farmers can undertake adaptation measures through land management practices (e.g. irrigation, crop variety choice, land use), but also take advantage of climate change in some areas.

Veneto Region has suffered in the past 20 years high soil sealing and the highest impact on SOC degradation is reflected by land use conversions from pasture/native vegetation to arable and intensive techniques. Having agriculture a major effect on Veneto Region and being down to its agricultural holdings to protect and sustain the soil ecosystem, without affecting its revenue and productivity: there is a great potential for an aware and sustainable use of its soil and resources.

Jumping form SOM declin as threat to the broader concept of soil status and protection in my region and in EU a small reflection on soil awareness issues learnt from my doctorate years needs to be discussed.

2015 will be the target date for Millennium Development Goals. The global campaign “Beyond 2015” has among its eight objectives eradicating extreme poverty and hunger and ensuring environmental sustainability. The Expo 2015 Milano “*Feeding the Planet. Energy for life*” will open its pavilions to the public in May the same year. In addition the whole year, as designated by the 68^{th} UN General Assembly, will be celebrated as the International Year of Soils. Despite this worldwide celebrations and acknowledgement, there is still a shocking ignorance amongst young people about where their food comes from and food security issues. Soil, as a natural resource, is still not widely considered as a playing actor in combating hunger, facing climate change, fresh water scarcity and biodiversity loss. Since the former EU Thematic Strategy for Soil protection many activities on soil research and awareness have blossomed in Europe. Soil expertise and local knowledge have built up a creative range of initiatives at primary, high school and university education levels. In the recent years, the concept of interdisciplinary and transdisciplinary for soil science has started to be accepted and the topic embraced by pedologists to team up with geographers, agronomists, biologists, chemists and urban planners. Official and informal networks of soil experts are starting to appear worldwide thanks to their willingness and ease to be connected. Despite this flourishing of innovative activities to promote the protection of our soil, soil science still remain non teacher friendly, no active learning, locally applicable, too costly, and publicly unintelligible, therefore not appealing. The way to capitalize on this, rather uncoordinated suite of positive examples offered by soil enthusiasts is to provide a common platform appropriate to all parts of the world, with a common consensus on soil issues to be covered and be brought to the table of consumers.

The Global Soil Partnership (GSP) is an interactive, responsive and voluntary partnership, open to governments, regional organizations, institutions and other stakeholders. One of the pillars of action aims to "Encourage investment, technical cooperation, policy, education awareness and extension in soil".

"*Keeping and putting carbon in its rightful place needs to be the mantra for humanity if we want to continue to eat, drink and combat global warming*"[45]

from the article -Peak Water, Peak Oil.. Now, Peak Soil? - Stephen Leahy, *Soil Carbon Sequestration* conference, Reykjavik, Iceland, 2013.

[45] http://www.ipsnews.net/2013/05/peak-water-peak-oilnow-peak-soil/

Acknowledgments

I am particularly grateful to

my supervisor, Prof. Francesco Morari for the opportunity to undertake my PhD and for supporting me from far away during my doctorate years;

my co-supervisor, dr. Luca Montanarella from the European Commission DG Joint Research Centre, headquarter of my PhD research;

my colleague and tutor dr. Emanuele Lugato for teaching me modelling, for keeping me on the right line and for the work done together under the CAPRESE project;

my colleague dr. Arwyn Jones for the work done together under the CAPRESE project, for the soil raise awareness activities developed together, for the technical and emotional support in my last year of PhD;

my colleague dr. Panos Panagos for involving me in the EIONET-SOIL project;

my former supervisor in the DG Agriculture, dr. Andreas Gumbert, initiator of CAPRESE project;

my former colleagues mrs. Thorunn Petursdottir, dr. Ece Aksoy and dr. Rannveig Guicharnaud for their emotional support;

dr. Gianluca Simonetti, mr. Giovanni Locoro, dr. Gergely Toth, dr. Riccardo Polese, mr. Michele and mrs. Martina Boschiero for their help for the the LUCAS soil survey and organic carbon lab analysis;

my university colleagues dr. Elia Scudiero, dr. Nicola Dal Ferro, dr. Elisa Cocco and dr. Giulia Florio for helping me from far away with the bureaucracy.

ARPAV - Osservatorio Regionale Suoli for providing data point information.

My PhD research was developed and funded by the European Commission DG Joint Research Centre, Ispra, Italy.