Estimating soil carbon sequestration potential in Portuguese agricultural soils through land-management and land-use changes: a tier 1 approach

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Abstract

It is widely accepted that, in order to limit global warming to 2ºC and to pursue efforts to stay below 1,5ºC, it is necessary to employ negative emission technologies (NETs). Soil carbon sequestration (SCS) is a NET with low energy and cost requirements with a potential to both contribute to climate change mitigation and promote adaptation of agricultural systems. For cropland and grassland soils, SCS can be achieved through adequate land-use and land management practices such as improved crop varieties, reduced tillage and no-till, conversion to irrigation and improved grasslands.

The CAP (Common Agricultural Policy) promotes agri-environmental measures and eco-schemes that reflect the growing concern of European policymakers in mitigating climate change, hence, the ability to measure, communicate and verify the effect of such agricultural practices on European soil becomes pressing.

This M.Sc. dissertation aims to be a preliminary study towards understanding how the CAP agri-environmental measures and eco-schemes influence SCS. Following IPCC's Tier 1 methodology, we provide: 1) estimates on the current SOC (soil organic carbon) content in mainland Portugal's agricultural soils (tC ha^{-1}); 2) sequestration/emission potentials (ΔC, tC y^{-1} ha^{-1}) which result from specific land management practices and land-use changes (transitions); and 3) estimates for the total national sequestration potential for each transition (ΔC, tC y^{-1}).

The results indicate a national theoretical maximum sequestration potential, in the top 30 cm of the soil of 0.06 MtC y^{-1} for a transition from full to no-tillage agriculture in annual crops, 0.04 MtC y^{-1} for a transition from rainfed to irrigated annual crops, 0.03 MtC y^{-1} when transitioning from annual crops to perennial crops and 0.39 MtC y^{-1} from natural to improved grasslands. For the transition from annual crops to perennial crops, some regions of Portugal exhibit a potential to emit rather sequester.

Lastly, we attempted to test the adequacy of IPCC estimates against in-situ sampled organic carbon (OC) data collected by EUROSTAT / LUCAS. We found a tendency for the IPCC Tier 1 methodology to underestimate SOC stocks in Portugal, which may indicate that: i) the tier 1 methodology should be improved to better reflect Mainland Portugal climatic and edaphic factors, especially in warm dry temperate conditions and areas with podzol soils, ii) the development of a higher tiered methodology should be prioritized, for which collective efforts for collecting soil data would be needed.

Keywords: recommended management practices, soil-based carbon dioxide removal, soil carbon sequestration, soil organic carbon, IPCC tier 1 methodology, soil emission and sequestration factors

Resumo

Para limitar o aumento da temperatura a 2ºC relativamente a valores pré-industriais, será necessário aplicar tecnologias de remoção de carbono. O sequestro de carbono pelos solos através da aplicação de determinadas práticas agrícolas e/ou conversão do uso dos solos, é uma tecnologia de remoção de carbono com baixos custos e baixo consumo energético, capaz de contribuir para a mitigar as alterações climáticas e promover a adaptação dos sistemas agrícolas às mesmas. Para solos com culturas anuais estas práticas incluem a redução da mobilização dos solos, a aplicação da sementeira direta, de rega, ou, para as pastagens, a melhoria das mesmas, através do aumento da diversidade das espécies de plantas e gestão adequada do pastoreio.

A PAC (Política Agrícola Comum) promove medidas agroambientais e eco-regimes que refletem a crescente preocupação dos decisores políticos europeus em mitigar as alterações climáticas. Assim, é bastante importante melhorar a capacidade de medir, comunicar e verificar o efeito de tais práticas agrícolas nos solos europeus.

Esta dissertação de mestrado apresenta-se como um estudo preliminar à compreensão do impacto das medidas agroambientais da PAC no sequestro de carbono, em Portugal Continental. Seguindo a metodologia *Tier 1* do IPCC, fornecemos 1) estimativas sobre o conteúdo atual de carbono nos solos agrícolas de Portugal Continental por hectare (tC ha^{-1}), 2) potenciais de sequestro/emissão anuais, ΔC, (tC y^{-1} ha^{-1}) que resultam da alteração de práticas específicas de gestão e/ou de alterações no uso dos solos (transições) e 3) estimativas para um total nacional teórico de sequestro de carbono por transição, destacando regiões onde estas práticas podem providenciar maior ou menor sequestro de carbono.

Os resultados indicam um potencial nacional teórico máximo de sequestro de carbono de 0,06 MtC y^{-1} ao aplicar a sementeira direta em culturas anuais, 0,04 MtC y^{-1} ao transitar de culturas anuais de sequeiro para culturas anuais de regadio, 0,03 MtC y^{-1} na transição de culturas anuais para culturas permanentes e 0,39 MtC y^{-1}, ao aplicar um regime de pastagens melhoradas em pastagens pobres. Para a transição de culturas anuais para culturas permanentes, algumas regiões de Portugal Continental apresentam um potencial de emissão de C em vez de sequestro, o que destaca a necessidade de ponderação ao aplicar certas práticas.

Por último, procurámos testar a pertinência das estimativas obtidas através do IPCC em refletir os valores de carbono orgânico (OC) obtidos *in-situ* pelas campanhas do LUCAS. Constatamos que a Metodologia *Tier 1* do IPCC subestima o conteúdo de carbono nos solos em Portugal, o que poderá indicar que: i) a metodologia *Tier 1* deverá ser melhorada para melhor refletir os fatores climáticos e edáficos de Portugal Continental ii) o desenvolvimento de uma metodologia de nível superior deverá ser priorizado, para o qual esforços coletivos serão necessários no sentido de coletar dados sobre os solos.

Palavras-chave: tecnologias de sequestro de carbono, sequestro de carbono pelos solos, carbono no solo, práticas de gestão recomendadas, metodologia *tier 1*

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Just like following the curriculum of the M.Sc. in Environmental Engineering, composing this thesis has also been an ongoing process of continuous challenge and enthusiastic discoveries. When I initiated this dissertation, my understanding of most of the subjects we here explore was limited. It is a notable achievement to reach the endpoint of this journey with new skills and knowledge and a thriving curiosity that inspires me to keep studying, learning, and researching about these topics, hoping to contribute in some manner to reducing knowledge gaps.

I would like to begin by expressing gratitude to Paulo Canaveira for his readiness in consistently answering and clarifying any of my doubts with insightful guidance and patient demeanour when I so greatly needed it; for reviewing my work and consistently offering constructive feedback, motivating me to go through any obstacles, and with his trust, strengthening my self-confidence in my work. I would also like to thank Tiago Domingos for his inspiration as a professor and critical thinker. There is no way I could have anticipated that attending his 'Big History and Sustainability' class would lead me to find such interest in reading, writing, and discussing subjects regarding climate change and human evolution, a practice that has revealed itself as a prolific outlet for my climate anxiety.

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Enthusiastic for what follows and reassured that the path forward will be exciting, challenging and as always, unknown.

Mariana Raposo,
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List of Acronyms

AFOLU	Agriculture, Forestry, and Other Land Use
BD	Bulk Density
CAP	Common Agricultural Policy
CDM	Clean Development Mechanism
CDR	Carbon Dioxide Removal
CH_4	Methane
CO_2	Carbon Dioxide
COP	Conference of Parties
DOC	Dissolved Organic Carbon
EAFRD	European Agricultural Fund for Rural Development
EU	European Union
FAO	Food And Agriculture Organization
GHG	Greenhouse Gas
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
JIT	Joint Implementation
LU	Land Use
LUCAS	Land Use/Cover Area Frame Statistical Survey
MAP	Mean Annual Precipitation
MARETEC	Marine, Environment and Technology Center
MAT	Mean Annual Temperature
MBC	Microbial Biomass Carbon
MC	Monte Carlo
MRV	Monitoring, Verification, and Reporting
MSs	Member States
N_2O	Nitrous Oxide
NETs	Negative Emission Technologies
NUTS	Nomenclature of Territorial Units for Statistics
OC	Organic Carbon
PET	Potential Evapotranspiration
RDP	Rural Development Policy
RMPs	Recommended Management Practices
SCS	Soil Carbon Sequestration
SIC	Soil Inorganic Carbon
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
TOC	Total Organic Carbon
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization

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1 Introduction

1.1 Climate change and the need to mitigate global emissions

Human activities, particularly, the combustion of fossil fuels, land-use change and agriculture, have led to an increase in greenhouse gas (GHG) emissions. Carbon dioxide (CO_2) emissions account for the highest portion of greenhouse gases in the atmosphere. Since 1751, the total additional emissions are estimated at 1.5 trillion metric tons of CO_2. Non-CO_2 GHGs such as nitrous oxide (N_2O) and methane (CH_4) - which further enhance global warming -, combined with emissions of CO_2, account for 2.5 trillion metric tons of carbon dioxide equivalent emissions since 1850 (IPCC, 2022).

The rise of GHGs in the atmosphere has had direct implications for the average global temperature, which has risen by an average of 0.08ºC per decade since 1880. According to the National Oceanic and Atmospheric Administration (NOOA), 2022 was the sixth-warmest year on record since 1880 (NOOA, 2023).

The consequences of human-led changes in the composition of the atmosphere impact Earth's systems vastly. According to IPCC's working-group I (WRI), changes in the state of the physical climate system such as warming of the atmosphere and ocean, diminished ice-caps, rise of the sea level and ocean acidification are "unequivocal" (IPCC, 2023). Current observed impacts which may be attributed to human-led climate change with "high confidence" include changes in ecosystem structures and species. Climate change has direct consequences on biodiversity loss, impacts in agriculture and food systems, health risks, as well as complex social and economic repercussions (Mukherji et al., 2021), such as the exacerbation of existing geopolitical conflicts, through climate-change related pressures, which are likely to increase if mitigation - efforts taken to reduce and prevent the severity of climate change, such as greenhouse gas emissions reduction - is not actively taken.

The first Industrial Revolution, which emerged in the late 18th century, was a transformative period marked by the widespread adoption of fossil fuel-powered machinery which replaced human and animal powered labour (Spier, 2010). This revolutionary shift fuelled the expansion of various industries, leading to increased productivity and the emergence of new economic sectors (Steffen et al., 2011). Advancements in transportation, particularly with the introduction of steam engines and railroads, facilitated faster movement of goods and stimulated the growth of global trade (Clark, 2012). Agriculture was another sector whose productivity grew thanks to the adoption of machinery, which revolutionized farming practices and contributed to increased yields. Alongside mechanization, the availability of chemical fertilizers facilitated land-use changes and intensified agricultural production, leading to improved efficiency and productivity in farming (Steffen et al., 2011).

This great acceleration laid the foundation for the current industrialised modern world by not only completely impacting the way we extract, produce, and consume but also the ecosystems with whom we interact whilst we take part in the vectorization of capital, goods and information, inherent to our current society. In fact, these changes are considered so impactful that within the scientific community many use, informally, the term *Anthropocene* to indicate the beginning of a new geological era (Steffen et al., 2011). Furthermore, the recent evidence of changes in climate patterns have brought into sharp focus the capacity of contemporary human civilization to influence the environment at the scale of Earth.

Our world and its 4.6 billion years of history (Spier, 2010) have sustained and endured massive changes: from the emergence of the first forms of life (~3.4 billion years ago), the rise and demise of different species as well as five large mass extinctions in the last 600 million years (Raup, 1986) and naturally occurring geological transformations and climate transformations. In this light, it is recognized that the current changes being observed are unprecedented and human caused (IPCC, 2023).

The consequences of climate change are experienced differently from region to region, and the response to anthropogenic climate change related risks lie essentially on the capacity of states' and regions to adapt and mitigate. The latter - reducing GHG emissions and enhancing Earth's sinks - has received greater attention, both from a policy-making and scientific perspective, since it is defended that mitigation benefits systems at a wider scale while enhancing protection of climate sensitive systems (Füssel & Klein, 2006). On the other hand, adaptation - which involves anticipating and responding to expected climate caused changes, through the use of infrastructure – is intended to be a means to counter the growing risks associated with climate change (Dow et al., 2013).

In the 1970s, concerns about the potential impacts of rapid population and resource use growth gained traction. The Club of Rome's 1972 "Limits to Growth" report and the establishment of the United Nations Environment Programme (UNEP) in 1985 through the Vienna Convention were important moments of this movement. The publication of "Our Common Future" in 1987 introduced the principles of sustainable development, while the formation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 during the Rio Convention further solidified our recognition of the human impact on ecosystems and climate. Through the 27 Conference of the Parties (COPs) held under the UNFCCC, and its latest treaty – the Paris Agreement – the world's governments have collectively acknowledged the urgent need to drastically reduce greenhouse gas emissions to limit global warming to well below 2°C, ideally close to 1.5°C, to prevent irreversible damage to our ecosystems, environment, and human well-being.

To achieve these drastic emissions reductions, significant changes need to be done in the way we extract, produce, consume, and dispose in all sectors of society. Globally, agriculture accounts for around 12% of total GHG emissions, after the energy and fuel combustion sector, which is by far the largest emitter, representing around 75% of total GHG emissions, as of 2020 (European Commission. Joint Research Centre., 2022; FAO, 2022). Tackling these two major sources of emissions should be a priority. Although agriculture releases significant amounts of GHGs to the atmosphere, there's a great potential to implement immediate emission reduction and sink enhancing management strategies (Smith et al., 2008).

1.2 The need for negative emission technologies

IPCC's Sixth Assessment Report (AR6), while exploring global pathways to limit temperature below 1.5ºC and 2ºC, establishes the need to immediately and drastically reduce emissions, achieving net zero (balance of emissions and removals) around, respectively, 2050 and 2070.

In both temperature pathways, net negative CO_2 emissions will be needed, which imply using Carbon Dioxide Removal (CDR) Technologies or negative emission technologies (NETs) (Fuss et al., 2018; Kriegler et al., 2014; Van Vuuren et al., 2018).

These technologies include: i) BECCS (bioenergy with carbon capture and storage), ii) DACCS (direct air carbon capture and storage), iii) enhanced weathering of minerals, iv) ocean fertilisation (manipulation of uptake of carbon by the ocean either biologically, v) biochar (converting biomass to recalcitrant biochar to use as a soil amendment) and vi) soil carbon sequestration through changed agricultural practices or/and afforestation and reforestation (Smith, 2016).

The development and implementation of NETs shows varied cost implications, energy requirements and water use (Smith, 2016), as well as other policy and governance factors, public perception and acceptance (Wenger et al., 2021), and possible social environmental risks of their own (Reynolds, 2018).

Soil-based carbon sequestration technologies, biochar, v), and changed agricultural practices and land-use, vi), show useful negative emission potentials, with lower energy and cost requirements (Fuss et al., 2018; Smith, 2016), when compared to other NETs. Furthermore, biochar and soil carbon sequestration may yield other co-benefits, such as improved soil quality, nutrient retention, and water cycling (Fuss et al., 2018).

In the following sections of this work, we will, therefore, explore soil carbon sequestration dynamics, global SOC stocks and potentials and how SCS has so far been promoted in distinct policies and mechanisms.

1.3 The global carbon cycle

Comprehending the intricacies of the carbon cycle, including its interconnected fluxes and crucial carbon sinks holds paramount significance. It not only enables us to gain a better visualization of carbon movement and the complex interplay amongst the various elements within the Earth system and the carbon cycle but also empowers the development of strategies to enhance natural systems' capacity for potentially mitigating the rate of anthropogenic CO_2 accumulation in the atmosphere (Falkowski et al., 2000).

There are two different velocities in the global carbon cycle, in which different elements of the earth system participate:

i. The fast carbon cycle, which encompasses interactions between the oceanic, atmospheric, geologic, pedologic and biologic pools and can be completed within years;
ii. The slow (or geologic) carbon cycle, which acts over timescales of millions of years, involving processes which are part of the rock cycle (Smith et al., 2015).

While changes in the CO_2 uptake of the slow carbon cycle are dependent on processes related to plate tectonics, the fast carbon cycle is largely affected by Anthropogenic activities, particularly, the burning of fossil fuels, deforestation, soil tillage, cultivation of organic soils, wetland drainage and burning of biomass (Lal, 2004a).

There are five main carbon pools acting in the fast carbon cycle. The oceanic pool, the largest sink, with a total of dissolved organic carbon 50 times greater than the atmosphere (Falkowski et al., 2000) and an estimated 38,000 Gt of C (Lal, 2004a), the geologic pool, the second largest, with an estimated 5000 Gt of C, followed by the pedologic (or soil C pool), representing a total of organic and inorganic carbon estimated at 2,300 Gt of C, the atmospheric pool, with an estimated total of 760 Gt of C, and lastly, the biologic pool which represents all the carbon contained in living organisms, estimated at 560 Gt of C (Lal, 2004a). The rate of exchange of atmospheric CO_2 with oceans and terrestrial ecosystems determines the overall rate of change of atmospheric CO_2; this rate is very much dependent on sink strength of the reservoirs, which regulate atmospheric CO_2.

Terrestrial ecosystems uptake CO_2 primarily through plant's photosynthesis, leading to C storage in organic matter which then decays and is consumed by organisms. As this process of uptake takes place, CO_2 returns to the atmosphere through different respiratory pathways such as respiration by plants, respiration by soil microbes (which oxidize plant derived organic matter) and through other disturbances such as fires.

1.4 Pedospheric processes that affect carbon content

The pedosphere lies at the interface between the lithosphere and the atmosphere. It is usually a one to two-meter-deep layer on top of the Earth's crust which interacts with the atmosphere, lithosphere, biosphere, and hydrosphere, and supports all biotic activity within the terrestrial systems.

There are two types of carbon pools in the pedosphere: soil organic carbon (SOC) and soil inorganic carbon (SIC). Predominant pedospheric processes that affect SOC content and the dynamic equilibrium of input and output of carbon in and from the soils can be grouped into two categories:

i. SOC enhancing processes - through biomass production (e.g. fresh plant residues), humification (soil organisms break-up and consume organic matter into smaller fractions which then enter the humus pool), aggregation and sediment decomposition; whereby organic residues become more resistant to further change, and

ii. SOC degrading processes - soil erosion, leaching, and soil organic matter decomposition (Lal et al., 2018; Weil. Ray R. Brady & Weil, 2016).

Soil organic matter (SOM) is comprised of plant, microbial and animal bodies at various stages of disintegration and refers to all the organic matter present in the soil. This complex soil component is a vital indicator of soil quality and fertility. Soil organic carbon (SOC) is a combination of labile (DOC – dissolved organic carbon), very labile (DOC, dissolved organic carbon, MOC, mineral organic carbon) and recalcitrant (or stable) C such as humus (MBC, microbial biomass carbon). SOC may also be referred to as "total organic carbon" (TOC) – the organic carbon fraction stored in the SOM – assumed to be ~ 58% of SOM (Ramesh et al., 2019).

The labile (or active) forms of carbon highly contribute to soil nutrient cycling, feeding the soil fuel web. With a low residence time (1-5 years), and high vulnerability to oxidation, this pool has a potential to accentuate CO_2 effluxes to the atmosphere. Unlike slow SOC pools (20-40 years residence time) or the passive pools (200-1500 years residence time) with highly stabilised carbon fractions, and hence highly resistant to microbial activity, labile forms of carbon are a reliable indicator of soil quality and productivity (Majumder et al., 2008).
We may observe the interactions between the terrestrial pool (pedologic and biologic pools) and the atmospheric pool as well as anthropogenic activities which mostly impact soil C sequestration (Figure 1-1).

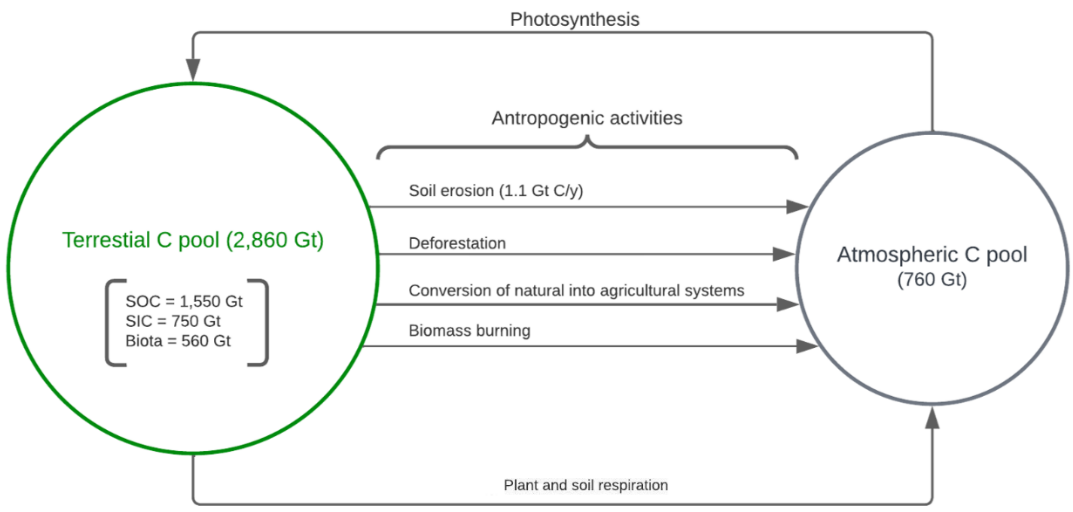


Figure 1-1 - Interactions between the terrestrial and atmospheric C pool. Adapted from Lal (2004)

1.5 Soils and soils mitigation capacity

Soils are essential for life on earth, playing a central role in determining the quality of the environment. They are a fundamental resource in the production of food, feed, fibre and fuels - soil nutrients, water, solar energy and CO_2 are converted through plant uptake and photosynthesis -, impacting the water cycle, through storage of water from rainfall as well as filtering of different substances, habitat provision for a diversity of organisms (soil biota) essential to decomposing organic material and regulating gas fluxes to and from the atmosphere (Palm et al., 2007). Globally, the organic carbon in soils accounts for an estimated 1,550 gigatons of carbon. Soils are the second largest active carbon sink after the oceans (38,000 Gt of carbon), storing more carbon than the atmospheric (760 GtC) and the biologic (560 GtC) pools together (Lal, 2004a).
Soils have an inherent capacity to sequester carbon, but also hold the risk to emit carbon, and are therefore crucial for climate change mitigation. Soil carbon sequestration (SCS) occurs when, through the application of specific land management practices - which may vary according to soil condition and soil type, regional climatic conditions and biomass availability (Amelung et al., 2020) land use type and other edaphic factors (Smith et al., 2020) -, the soil organic carbon (SOC) increases, resulting in a net removal of CO_2 from the atmosphere (Fuss et al., 2018). Such specific

land management practices aim to contribute to gaining and maintaining soil C, by increasing C inputs and/or reducing C losses, assuring a positive C balance, thereby promoting SCS. Yet, confusion persists about the specific set of actions that should be taken to both increase sinks with and reduce emissions from land use activities (Griscom et al., 2017). Contrary, soil emissions occur when processes that degrade soils and soil organic matter take place, such as erosion, land-use changes (such as deforestation and biomass burning), excessive soil disturbance, continuous monoculture and intensive cropping (Lal, 2004a, 2011).

1.6 Potential for carbon sequestration in agriculture

Global SOC stocks vary spatially, with most of the stocks being stored at northern latitudes, particularly, in the northern permafrost regions (Scharlemann et al., 2014). Similarly, for croplands globally, SOC stocks are generally lower in the tropics where it is hotter and/or drier, and higher in the cooler, wetter, more northerly latitudes: the regions of North America, Scandinavia, Russia and Europe currently store the greatest amount of carbon on cropland (Zomer et al., 2017).

Scharlemann et al. (2014) estimated soils carbon stock to be approximately 1,500 Gt of organic carbon globally, from a comprehensive review of 27 studies, spanning from 1950 to 2013. Considerable variability was observed, with estimates ranging from 504 to 3000 Gt of C (Scharlemann et al., 2014). Such variability is a consequence of factors such as differences in sampling methods, estimation methods, soil profiles and climate databases and their spatial resolution, and other land-use and geographic characteristics (Scharlemann et al., 2014).

Lal. et al. estimated the total C soil loss due to land cultivation to be one-half to two-thirds of the original SOC pool, with a cumulative loss of 30–40 tC/ha (Lal, 2004b).

Sanderman et al., estimated SOC loss of 75 Gt C in the top 1 meter, and 133 GtC in the top 2 meters of the soil, due to land-use change, over a period of 12,000 years, a mean loss of 8.1% in the top 1 m (Sanderman et al., 2017). Regrettably, we are unable to compare this mean loss to the one advanced by Lal et al., since the latter does not provide a mention to soil depths. While various estimates have been proposed, historical losses of Soil Organic Carbon (SOC) resulting from human land-use underscore the significant potential for SOC restoration in carbon-depleted soils through proper land management techniques.

The estimates of global potentials for SOC sequestration also show considerable variation (Amelung et al., 2020; Freibauer et al., 2004; Scharlemann et al., 2014). Based on a review of 22 papers conducted by Fuss et al., it was found that the estimation of soil carbon (C) sequestration potential varies depending on the assumptions made regarding available land area. When a scenario with greater available land area is considered, the estimated potential for soil C sequestration exceeds 7 Gt CO_2 per year. Conversely, when a more "realistic" approach is adopted, which accounts for the fact that not all land is available for land management due to land-ownership restrictions and other feasibility constraints, lower C sequestration values are obtained. This review ultimately resulted in an estimation of the global technical C sequestration potential at approximately 3.7 Gt CO_2 per year, until 2050 (Fuss et al., 2018).

Such a wide range in estimated global SOC stocks and SCS potentials highlights the need for continued improvements in data collection and processing to derive better estimates which correctly orientate policy and inform land management decisions (Scharlemann et al., 2014). Furthermore, global sequestration potentials should be approached with caution since limitations such as economic factors or soil management factors (such as private/individual land-ownership) may damper the implementation of the needed land-use or land management practices towards soil carbon sequestration (Amelung et al., 2020).

Turning to Europe, agricultural land accounts for nearly 40% of the total area (157 million ha), of which 62% were used as arable land (98.1 million ha), and 30% as permanent grassland (48 million ha) (European Commission. Statistical Office of the European Union, 2020).

An analysis on "Agricultural potential in carbon sequestration" requested by the DG AGRI of the European Commission, estimated carbon stocks in the EU-27 soils to range from **34 Gt** in the top 20 cm, to **75 Gt of C** in the top 30 cm, with uneven spatial distribution, with carbon rich soils in the Nordic and Northeastern countries and depleted southern carbon southern soils. From the total SOC stocks, 31,7% lie on agricultural soils, with 21,4% in cropland only and 9,3% in grassland (Andrés, P., 2022).

As for SOC sequestration potentials, a 2004 review article by Freibauer et. al. (2014), estimated a technical and economic carbon sequestration potential for cropland and grassland soils of 16-19 Mt C y^{-1} (~58.7-69.7 Mt CO_2 y^{-1}), for the period 2008 to 2012, for the EU-15[1], as a result of a conversion from a "business-as-usual scenario" to application of measures such as the introduction of perennials (grasses and/or trees) on arable set-aside land, and zero tillage or conservation tillage (Freibauer et al., 2004). The study highlights that achieving efficient carbon sequestration requires soil and climate adequate adoption and implementation of land-use and management techniques.

While specific literature on the topic of soil carbon sequestration in Portuguese cropland and grassland is limited, studies on the enhancement of carbon stocks of the Mediterranean basin are predominant, which we may use as a reference for understanding possible soil C enhancement strategies in Portugal Mainland.

In the Mediterranean region, several long-term experiments have reported a positive impact in the use of perennial crops and management practices such as medium-tillage or no-tillage, residue mulching, extended crop rotation, and cover cropping as strategies contribute to the soil C stock enhancement (Álvaro-Fuentes et al., 2009; Ordóñez Fernández et al., 2007). Consequently, soils in the Mediterranean region have a substantial potential to function as carbon sinks when subjected to appropriate management practices (Moukanni et al., 2022).

Experimental trials in a maize production in Campania (Italy), from 2006 to 2008, concluded that reduced tillage showed a reduction of GHG emissions from soil bacterial activity in comparison to conventional tillage, with a more significant reduction in CO_2 emissions as compared to N_2O

[1] the 15 Member States of the European Union as of December 31, 2003: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom.

emissions (Forte et al., 2017). The findings of this study suggest that reduced tillage can represent consistent GHG benefits for Mediterranean croplands.

A 20-year experiment established in 1986 on a rainfed Mediterranean vertosol in Southern Spain with five different wheat crop rotations, concluded that in general, crop rotation intensification and no-tillage increased SOC sequestration overtime (López-Bellido et al., 2010).

As for the use of cover-crops to promote SOC sequestration in the Mediterranean basin, a knowledge gap is yet to be filled to understand how relevant this strategy can actually be deployed to promote soil C sequestration as well as identify the cover crop species with greater contribution potential (Moukanni et al., 2022).

For grassland in Europe, and especially in the Mediterranean basin, the abandonment and transformation of cropland areas into grasslands[2] and agroforestry systems has been promoted with the goal of reducing surplus agricultural production and enhancing soil C (Carranca et al., 2022). Portugal's grassland systems may be divided in three types: natural grasslands (no management), fertilized natural grasslands (same species and varieties of spontaneous grasses and legumes as the latter, but suffer fertilization and shrub control) and sown biodiverse permanent pastures rich in legumes (SBPPRLs). Teixeira et al. (2015) developed a calibrated model using 5 years of soil analysis from 8 different sampling sites in Portugal Mainland which concluded that sown biodiverse permanent pastures rich in legumes (SBPPRLs) offer the highest SOC enhancement potential when compared to the other two grassland system types.

Portugal's given importance on animal farming and its focus on pasture management to achieve the goals of the Kyoto Protocol has been reflected in policies and funding of grassland management projects. From 2009 to 2014, the Portuguese government paid farmers through the Portuguese Carbon Fund – Terraprima (www.terraprima.pt/) projects, which supported SBPPRL (Sown Biodiverse Permanent Pastures Rich in Legumes) farmers to improve degraded pastures and increase soil carbon sequestration (Teixeira et al., 2015). By 2014 SBPPRL occupied 4% of the national agricultural land, leading to an estimated sequestration of 1.54 million tons of CO_2, if otherwise payments had been absent (Teixeira et al., 2015). Recently, Ravaioli et al. (2023), using an agent-based model (ABM), confirmed the previously obtained result for the additional sequestration impact of the project considering the same period (1.54 million tons of CO_2e) (Ravaioli et al., 2023).

From 2011 to 2014, another PFC funded Terraprima led project promoted the adoption of non-destructive shrub encroachment control methods which protect soil from erosion through the adoption of no-tillage techniques in various agroforestry systems (Domingos et al., 2021). The project counted with the participation of 400 farmers in 80,000 hectares of land, leading to an estimated sequestration of 0,5 Mt of CO_2 (Valada, 2014).

[2] 'pastures' and 'grasslands' are used interchangeably for simplification purposes.

1.7 Promotion of carbon sequestration in agriculture

The European Green Deal

The European Green deal is a recognition of the need to reduce emissions and adapt to climate change's most pressing issues by setting a 55% emission reduction target by 2030 (compared to 1990) and reaching zero net emissions by 2050. The commission constructed it's work programme around the areas of clean affordable energy, circular economy, agriculture and fisheries, biodiversity, sustainable and smart mobility and zero pollution (Wrzaszcz & Prandecki, 2020).

Overall, and according to the EEA (European Environment Agency), European GHG total net emissions have shown a decaying tendency, from 1991 to 2021, with 2020 as the year with the lowest total net emissions (EU-27)[3].

In 2021 the European Commission launched the "EU soil strategy for 2030" which set a framework for sustainable soil management, oriented towards restoration of soils both as a vector of the already established "EU biodiversity strategy for 2030" - which focuses on reversing the degradation of ecosystems and avoiding biodiversity decline - and as a climate change mitigation vector through promotion of SOC sequestration and GHG emission reduction, contributing thereby to the objectives of European Green Deal.

The "medium-term objectives by 2030" include the achievement of EU net greenhouse gas removal of **310 million tonnes of CO_2 equivalent in the year 2030** (310 Mt CO_2eq year^{-1}) for the land-use, land-use change and forestry sector (LULUCF) (European Commission, 2021), an important mitigation achievement if the EU-27 aim to reduce its net GHG emissions by at least 55% by 2030, compared to 1990, and as agreed in EU Climate Law (Andrés, P., 2022).

Although **55%** of the mitigation potential of the agricultural sector in Europe relies in agricultural soils and manure management (Andrés, P., 2022), a great constraint to verifying these effects and fairly compensate farmers for their achievements is the current limitations in MRV (monitoring, reporting, verifying), which bring about high costs and require intensive labour and time-consuming sampling techniques.

Despite the existence of detailed national SOC datasets by several European Union (EU) Member States, a consistent C stock estimation at EU scale remains problematic (Amelung et al., 2020; Lugato et al., 2014). In fact, there is a need for studies which cover qualitative and quantitative land-use and land management change effects on SOC across Europe in a way that is consistent and representative of the full spectrum of differences in soil type, soil degradation and climates (Jones et al., 2005; Smith et al., 2020).

Soil C sequestration capacity is limited by mechanisms of carbon sequestration, sink saturation reach, non-permanence (to effectively sequestrate carbon and maintain SOC levels even after sink saturation, agricultural land management practices must be permanent), and land-availability (Freibauer et al., 2004). Therefore, the objectives posed by the EU Union through their soil strategy show tremendous ambition. To achieve them, robust frameworks that can provide action-

[3] The year of 2020 is also affected by the COVID-19 pandemic and lockdown responses by governments.

oriented policies and promote knowledge transfer, research investment and appropriate financially sound schemes, as well as mechanisms of continuous verification, evaluation, and improvement are required.

The CAP

The EU Common Agricultural Policy (CAP) is one of the world's largest agricultural policy packages and the EU's longest prevailing one. Established in 1957 in the Treaty of Rome, its initial purpose was to increase agricultural yields, guarantee a fair standard of living for farmers, stabilize markets, ensure a balance between food supply and demand and harmonize competition rules across all countries by manipulating producer prices, whilst imposing production controls (quotas or set aside (Freibauer et al., 2004). Over the years, the CAP has guided member states (MSs) policy making process towards improving food quality, while integrating biodiversity conservation, environment focused action as well as attempts at promoting rural development through financial support which has been based on direct payments to farmers, usually following area (or animal) based payments (*Timeline - History of the CAP*, 2021).

The CAP consists of two pillars:

Pillar 1 consists of income support and market measures. Income support is granted through different types of direct payments (€40.4 bn., 69.4% of CAP in 2019), mostly paid per hectare or per animal, which are conditional on compliance with various regulations including environmental aspects. This type of direct support aims to ensure that MSs maintain farming activities adapted to their climatic situation and that farmers receive support in return for meeting certain environmental goals. Since the 2013 CAP reform, these direct payments became linked to 'Greening' and were proposed to support and reward farmers who were able to accomplish good environmental performance and deliver positive externalities (European Commission, 2019), including practices such as crop diversification, maintaining ecological focus areas on their land, and maintaining the share of permanent grassland, which would generally contribute to soil C sequestration. Market measures, on the other hand exist to counter-balance high price volatility in agricultural markets and is established by the common market organization (CMO) regulation and involves issues related to international trade, rules on marketing of agricultural products and other policies and tools that help improve functioning of agricultural markets.

Pillar 2 relates with Rural Development Policy (RDP) and is co-financed by the European Agricultural Fund for Rural Development (EAFRD) and national or regional budgets. This pillar provides funding for various measures, including agri-environmental schemes, investments in farm modernization, rural tourism, support for young farmers and initiatives promoting rural diversification and environmental sustainability. Carbon sequestration and other climate mitigation strategies are promoted in agri-environment schemes such as 'organic farming', 'soil conservation' and 'extensive pastoral farming'. As of 2021, the specific measures and priorities under Pillar 2 can vary between EU member states as they have the flexibility to design and implement programs based on their regional needs and priorities.

Carbon Markets

Since the Kyoto Protocol in 1997, carbon markets have emerged as one of the main policy-economic tools in global efforts to address climate change (Böhm et al., 2012). They come in two main species: ‘cap and trade’ and ‘project-based’.

Cap and trade systems involve an authority (such as a government) setting a ‘cap’, i.e., a maximum allowable aggregate total quantity of emissions, to which it is given a corresponding number of allowances to emitters. The authority then monitors emissions and penalizes emitters which do not comply with such requirements. The ‘trade’ aspect arises to allow those for whom reductions become too expensive to buy allowances – i.e., carbon credits – rather than incur in steep costs. The ‘trade’ happens between these and the ones to whom reducing emissions is relatively easy, and may thereby, sell their allowances and earn money. Currently, cap and trade systems or carbon credit trading mechanisms are in place in Europe and North America, such as the EU ETS (European Trading System).

Project-based systems - such as the Kyoto mechanisms Clean Development Mechanism (CDM) - allow for the development of a projects which guarantee additional emission reduction and may be held between a developing country entity and a corporation, government, or bank, whereby the latter may obtain carbon credits.

In the agricultural sector, carbon-credit systems could allow agricultural producers to earn an extra revenue through selling their surplus of carbon credits (which could be obtained via actions that enhance the soil carbon or biomass pools) to producers who emit higher amounts of GHGs. Agricultural carbon-credit systems are still at early development stage but have been gaining some relevance over the last years. Just recently, the European Commission have proposed the creation of a Carbon Removal Certification Framework (CRCF) which strongly focuses on ‘carbon farming’ activities. Nevertheless, many argue that ‘carbon farming’ may be misleading, since measuring and estimating carbon sinks or carbon sequestration potentials is a challenging task and so is the monitoring and verification process that should follow the application of recommended management practices (RPMs) or land-use conversion. Furthermore, individual land managers and farmers do not focus on sequestering C, but on agricultural production, hence, payments for services for the sequestration of additional SOC need to be such that they compensate for the extra efforts (Amelung et al., 2020).

In the absence of proper mechanisms for verification and ongoing monitoring of activities, carbon markets can ultimately undermine the essential efforts to mitigate climate change.

1.8 Objectives

Portugal does not yet have a systematic soil monitoring network with repeated soil sampling data. This thesis tries to overcome this problem by using IPCC’s tier 1 methodology, as described in the 2019 IPCC Guidelines for National GHG Inventories, to get a better understanding of the potential for soil carbon sequestration in Portuguese cropland and grassland soils. The main goals of this work are to:

- Estimate SOC stocks in mainland Portugal and how they relate to climate and soil types in different regions of the country.
- Identify land management and land-use strategies that are better suited for soil carbon sequestration in specific regions of mainland Portugal.
- Test the adequacy of the IPCC Tier 1 methodology by comparing results with in-situ samples and a modelled approach.

1.9 Structure of the work

The State of the Art section of this thesis explores the impact of different land-use (section 2.1) and land management changes (section 2.2) in SOC stocks globally. Section 2.3 describes with greater detail the various management options towards SCS in cropland, while section 2.4 highlights management options for grasslands. In section 2.5 we mention the current state of the art methods used to measure and estimate soil carbon stocks as well as limitations to them. In section 2.6 we refer some of the limits to SCS and wrap up our discourse in 2.7.

In section 3 we dive into the materials and methods used in this thesis (see Figure 1-2). We start by describing with detail the different steps followed to collect and process data (section 3.2), followed by a General overview of the IPCC Guidelines (section 3.3) where we mention some of the assumptions and limitations of the method. We then continue with a detailed description of the different steps in our approach of the IPCC Tier 1 Methodology (section 3.4), which encompasses:

- Obtaining Climate Types in Mainland Portugal and processing them to match the IPCC's pre-determined categories;
- Obtaining Soil Types Mainland Portugal and processing them to match the IPCC's pre-determined categories;
- Assigning a Reference SOC Stock Level, SOC_{REF} (tC ha^{-1}), to each of the 22,139 points in EUROSTAT's 2x2 km LUCAS grid in Mainland Portugal, representing the SOC that would be present in undisturbed conditions, under each specific soil and climate type;
- Estimating Baseline SOC Stock Levels, $SOC_{Baseline}$ (tC ha^{-1}), in all 7,184 LUCAS points with cropland or grassland land-uses, representing the expected equilibrium SOC levels under 'default management conditions', considering 2018 land-use data;
- Estimating SOC Sequestration or C emission factors per year, ΔC (tC ha^{-1} y^{-1}), an estimation of emitted or sequestrated C for **four** main transitions/land-uses: Annual Crops, "Full-Till" to "No-Till" (Transition 1), "Rainfed Crops" to "Irrigated Crops" (Transition 2), "Annual Crops" to "Intensive Permanent Crops" (Transition 3), "Natural Poor Grasslands" to "Improved Grasslands" (Transition 4), over a twenty-year period of application of such practices (from 2018-2038).

- Estimating the uncertainty and possible variability of the estimates, using Monte Carlo Simulations of emission/sequestration potentials of all transitions, and the uncertainty ranges provided by the IPCC for each variable;

In section 3.5 we estimate a maximum Portuguese national sequestration potential for each transition, by combining the emission/sequestration factors previously obtained from simulated land-use and land management changes (transitions) with the potential area of application of each change, using area statistics provided by the Portuguese National Institute of Statistics (INE). Finally, in section 3.6, we attempt to validate the figures obtained in this work by comparing $SOC_{Baseline}$ with in-situ soil organic carbon (SOC) levels measured in the surveys from 2009, 2015, and 2018 of LUCAS (Land Use/Cover Area frame statistical Survey) Database and our sequestration/emission values with values obtained with a modelling approach by Morais et al. (2019).
Data processing, computation, and visualization were carried out using Microsoft Excel v.16.0, QGIS 3.0, and Python 3.9:

- Excel was used to classify the climate and soil types of each point, and to compute $SOC_{Baseline}$, Emission/Sequestration factors (ΔC), National Sequestration Potentials and to evaluate the Tier 1 methodology Adequacy.
- QGIS was employed to process data, fill in data gaps, and visualize the results through geospatial mapping. All maps presented both in the Methodology as in the Results sections were generated using QGIS 3.0.
- The Jupyter Notebook (https://jupyter.org/) was used write and run the Python (Version 3.9) code for the Monte Carlo simulations of different estimations.

We show the results obtained with this approach in section 4 and wrap up with the main conclusions and recommendations of future work, in section 5.

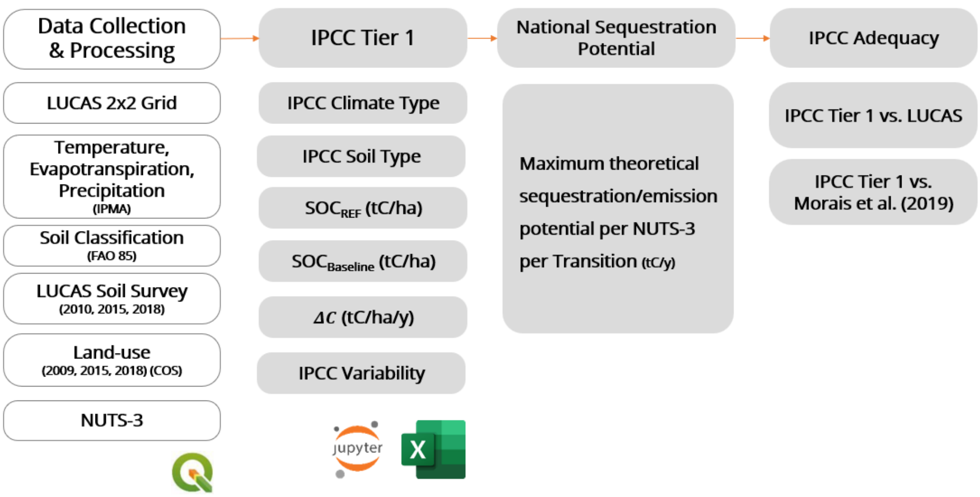


Figure 1-2 – Methodology Structure

2 State of the Art

Global soils have been degraded, having lost a great part of their SOC through expansion of agriculture, pastoralism, and land-use conversion from native ecosystems such as peatlands, grasslands and forests to arable land. Most recent literature estimates agricultural land uses have resulted in the loss of up to 133 GtC (~488 $GtCO_2$) from the soil (Sanderman et al., 2017).

It is important to highlight two distinguished soil types which have very different soil organic C content: mineral soils - with 1-5% of organic C - and organic soils - such as peatlands and wetlands, which contain more than 20% of global soil organic C in their top 30 cm, but occupy only 3% of land surface (Rumpel et al., 2020). Due to the difference in SOC stock of organic vs. mineral soils, their C sequestration potential varies as well as management practices indicated for SOC enhancement. While for SOC depleted soils most land management practices focus on efforts to increase C input and reduce C output, for organic soils, most practices focus on avoiding C loss (Amelung et al., 2020), through careful management of water levels. Organic soils have no material expression in Portugal, and therefore we focused only on mineral soils in this thesis.

There is a wide range of land-use and land management options oriented towards soil carbon sequestration which provide different benefits according to climate and soil variables. It is a focus of this thesis to understand how these impact SOC levels in mineral soils, map and describe the different land-uses, land management practices, their benefits, and co-benefits as well as possible trade-offs. We are thereby interested in learning how literature describes how certain land-use changes and land-use management strategies impact soil organic carbon content.

2.1 Land-use change and soil carbon stocks

Land-use change refers to the process of altering the purpose or function of a piece of land, involving, usually, modifying the way the land is used, developed or management. In this dissertation, when we refer to "land-use change", we aim at the less broad sense the expression, i.e., to situations of conversion of land such as conversion from forest or grassland to cropland. Land-use change can cause a change in land cover and, consequently, a change in carbon stocks, but the impact of such changes varies spatially and with conversion type.

Guo & Gifford (2002) reviewed 74 publications covering 16 countries to evaluate how different land-use transitions (from forest to pasture, from pasture to secondary forest, from pasture to plantation, from crop to secondary forest, from pasture to crop and from crop to pasture)[4] impacted soil C. This meta-analysis concluded that soil C stocks significantly increased (C sequestration) after the conversion of land from forest to pasture (+8%), crop to plantation (+18%), crop to secondary forest (+53%) and crop to pasture (+19%). The decline in SOC stocks (C emissions) was observed in conversion of land from pasture to plantation (-10%), forest to plantation (-13%), and from forest and pasture to crop (-42% and 59% respectively). Specifically, they concluded that when native forests are converted to cropland, soil C stocks are halved in the topsoil but not

[4] Authors define 'forest' as native forest, 'pasture' as land used for grazing purposes (including natural grassland), 'crop' as any cultivated land for food and fibre products, 'secondary forest' as naturally developed forest on abandoned land and 'plantation' as any human-induced forest plantation.

affected at depth, and, when cropland is converted to plantation, there is a partial recovery in soil C stocks, recovery which may be greater if conversion happens from cropland to naturally regenerated secondary forest. Interestingly, when native forests are cleared for pastures, soil C stocks do not generally decline and may even increase in areas with 2000–3000 mm $year^{-1}$ of annual precipitation (Guo & Gifford, 2002).

Another global meta-analysis of 385 studies on land-use change in the tropics concluded that the highest SOC losses from land-use change were caused by land conversion of native forest into crop land (−25%), and that SOC losses may be partly reversible if agricultural land is afforested (+29%) or under cropland conversion into grassland (+26%). Similarly, authors Don. et, al 2011 also concluded that secondary forests store much less carbon than native ones (Don et al., 2011).

While reforestation is an effective method to increase SOC stocks, another land-use change option towards soil carbon sequestration is the 'perennialization' of agricultural lands – conversion of annual crops to perennial crops – which may also enhance food security and ecosystem services (Glover et al., 2010). By modelling temporal changes in SOC and considering the effect of climate, soil properties and land use, Ledo et al. concluded that a transition from an annual to a perennial crop generally resulted in an average gain of 30% in SOC, after 20 years or more after conversion (Ledo et al., 2020), highlighting that SOC changes are highly affected by temperature regimes, whereby higher temperatures in warmer/tropical areas are negatively correlated with SOC changes. This results in a severe limitation for positive SOC balances in warmer climates.

Nevertheless, and although evidence exists that certain land-use conversions may benefit soil C sequestration, there is still a significant knowledge gap to be filled due to uncertainties related with discrepancies in experimental designs, estimation methods used, wide location ranges (Ledo et al., 2020) and poor or insufficient (such as shallow sampling depth) and representativeness (Don et al., 2011), which should be counteracted with efforts to better obtain, process and analyse data, specially, in locations where this data is more scattered or poorly represented.

2.2 Land management practices and soil carbon stocks

There isn't a one-size-fits-all approach to the question of which land management practices should be used to promote soil carbon sequestration, and, in fact, sequestrating SOC requires tailored approaches which consider soil group, climatic region, soil degradation status as well as other site-specific factors. Different land management practices will have different potential trade-offs (Scharlemann et al., 2014) such as expansion of water use (e.g. use of irrigation) (Rumpel et al., 2020) or the increase in N_2O and CH_4 emissions (Powlson et al., 2011).

Application of Recommended Management Practices (RMPs) such as adoption of conservation tillage, cover crops and crop residue mulch, nutrient cycling - including use of compost and manure -, the application of sustainable management of resources and conversion of arable land to grassland or forest land to improve soil C sequestration (Lal, 2004), have been globally popularised and promoted through initiatives such as "4p1000 initiative", launched at the UNFCCC 21st conference of parties in 2015 (COP21), highlighting that an increase of 0.4% per year in SOC would have a potential to counterbalance the long-lasting increase in atmospheric CO_2 (Rumpel

et al., 2020). Many of these RMPs may also have other co-benefits such as improvement of food security and climate change adaptation of agriculture, providing win-win results.
Increasing the soil C content can be achieved by increasing the C input, decreasing the C output or a combination of both, through improved land-use and land management strategies. Increasing C input may be achieved with fertilisation of land with animal manure, the use of crop residues, crop rotation (Freibauer et al., 2004) or the introduction of biochar to soil (Scharlemann et al., 2014; Smith, 2016). The input increase with organic amendments (such as manure, compost or biochar) should be secured through on-site available inputs in order to avoid "carbon leakage" (an expression borrowed from carbon markets): if a meaningful increase of C accumulation should happen in one region it should be so that it avoids simultaneous reductions in SOC at another location (Amelung et al., 2020).
Decreasing the C output may be achieved through a reduction in the disturbance of soils, through strategies like reduced or zero tillage, set-aside land or conversion of arable land to grassland and cultivation of perennial crops - which, unlike annual crops, do not require replantation. Some strategies like the use of cover-crops may have a two-way effect, both enhancing soil inputs and decreasing disturbance of soils.
Certain management practices have raised concern regarding their possible effect in increasing other non-CO_2 GHG emissions (Freibauer et al., 2004; Rumpel et al., 2020). These include N_2O emissions following mineral fertilisation and N_2O and CH_4 emissions from ruminant livestock, which have a greater global warming potential than CO_2 (x273 for N_2O and x28-34 for CH_4, in a 100-year period) (Pachauri et al., 2015). Hence, the application of mineral fertilisers should be synchronised with plant uptake and site-specific, pedoclimatic conditions in order to minimise gas phase contamination or contamination of water bodies, since the maximisation of C sequestration should not be done by maximising N leakage (Amelung et al., 2020).
For agricultural soils which have lost a significant part of their carbon content there is a high potential for improving SOC content. Hence, finding the right management practices which promote the increase of organic inputs and enhance soil processes that protect SOC is of great relevance to guarantee that soils work as a carbon sink rather than a source (Ramesh et al., 2019).
Traditional methods which have contributed to soil organic carbon depletion with consequent emission of CO_2 and other GHGs to the atmosphere include biomass burning and residue removal, conventional tillage, continuous monoculture, intensive cropping, bare soils, indiscriminate use of pesticides and intensive use of chemical fertilisers, among others (Lal, 2004a).
The reduction of SOC pools in cropland soils also enhances soil degradation. Physical degradation happens through the decline in soil structure, reduction in aggregation, compaction, as well as chemical degradation - with acidification of the soil, nutrient depletion - and biological degradation - with decline in soil biodiversity. Therefore, guaranteeing the enhancement of SOC pools in cropland soils not only contributes to mitigation of emissions but also to improving the overall soil ecosystem and health.

2.3 Cropland management practices

Cropland management strategies to improve SOC can be clustered into different general practices which work towards SOC sequestration and GHG emission reduction through distinguished mechanisms of action, which may overlap in some instances. Smith et. al have summarised these various mitigation options (Smith et al., 2008) as follows:

Agronomy

Improving inputs of C can be achieved through enhancing crop residues such as shoots and roots, through intensification of crop yields (Yang et al., 2013). These include specific practices such as the use of improved crop varieties, extended crop rotations (notably in perennial crops) or avoiding bare fallow.

Reducing GHG emissions can be achieved by adopting less intensive cropping systems such as the use of legume crop rotations which reduce reliance on fertilizers and other inputs.

The agronomic use of cover crops as green manure also enhances C input to soils (Poeplau & Don, 2015) and may also consume plant-available N leftover by the preceding crop, thereby reducing N_2O emissions.

Nutrient management

Improving the efficiency of the use of nitrogen by crops has the potential to reduce N_2O emissions as well as indirectly reduce emissions of CO_2 from manufacture of N fertiliser.

This can be achieved through precision farming techniques such as adjusting application based on precise estimation of crop needs or placing N into the soil, making it more accessible to crop roots. Careful N fertiliser use can provide GHG emissions' reduction as well as cost reduction.

Opting for organic fertilisation through the use of compost or animal manure may also enhance soil C sequestration (Freibauer et al., 2004) as well as increase stable soil aggregates, if applied long-term (Ramesh et al., 2019).

Tillage

Tillage practices greatly influence cropping systems dynamics such as crop yields, crop root growth and soil erosion. It is widely believed that soil disturbance by tillage is a primary cause of historical SOC loss.

Conservation tillage practices such as reduced till and no-till have been popularised for their potential for atmospheric CO_2 sequestration as well as reduction of other GHG emissions. Although this applies in a lot of cases, recent studies have found evidence that points to results which are less efficient than expected (Yang et al., 2013).

Some studies explore and question the actual efficacy of no-till agriculture for increasing C in soils as well as its impact on crop yields, e.g., questioning the sampling methods and protocols used to determine SOC sequestration. For instance, Baker et al. highlights that in studies where conservation tillage was found to sequester C, soils were only sampled to a depth of 30 cm or

less, and where a greater depth of sampling was pursued, SOC content showed lower concentrations in deeper layers in comparison to conventional tillage (Baker et al., 2007).
As for crop productivity, a meta-analysis of 74 published studies by Ogle et al. found that it can be reduced with adoption of no-till vs. full tillage, particularly in cooler and/or wetter climatic regions (Ogle et al., 2012).
Thereby, the efficacy of conservation tillage practices in increasing soil C content may be smaller than previously claimed for temperate and cold regions (Powlson et al., 2011).

Water management

According to the Food and Agriculture Organization (FAO) Report on The State of the World's Land and Water Resources for Food and Agriculture, twenty percent of managed cropland worldwide requires irrigation (FAO, 2022, p. 20) and irrigated production is responsible for approximately 40 percent of agricultural output (FAO, 2018). Drought-prone soils rely on application of irrigation to increase biomass production (Ramesh et al., 2019). With climate change and drought frequency increases, irrigation needs are therefore likely to become greater.
Water management and judicious use of irrigation are essential to guarantee yield consistency and consequent growth of aboveground material and root residues, in order to enhance SOC concentration (Smith, 2008). Multiple studies have shown that irrigation of annual and perennial cropland effectively enhances SOC (Morais et al., 2019; Sainju et al., 2008; Trost et al., 2013). In specific regions, irrigation combined with other practices such as leaving crop residues on field may lead to even higher sequestration rates than grasslands (Morais et al., 2019).
Although it is not the focus of this thesis to explore with great detail how other factors impact SOC, it is important to mention that chemical properties (such as pH, nutrients availability or redox potential), biological properties, such as soil microbial community (bacteria, actinomycetes, fungi, algae, protozoa, and nematodes) and enzyme activity, geological factors such as topography, altitude, soil type and soil physical properties such as bulk density, soil minerals, moisture, texture and structure, are important drivers of soil organic carbon dynamics (Ramesh et al., 2019). Land management practices have the potential to affect some of the aforementioned factors, such as chemical properties, soil microbial community and other physical properties.

2.4 Grassland management practices

Grasslands cover 40% of the earth's land surface, store approximately one third of the global terrestrial C stocks and, having suffered past C losses due to agricultural use, have the potential to act as C sequestrators (Bardgett et al., 2021; McSherry & Ritchie, 2013). Restoration of grasslands is possible and can bring about both enhancements in SOC sequestration as well as its capacity to be a container of biodiversity, including many iconic and endemic species, and to provide a wide range of ecosystem services.
Conversion of grasslands to forest or croplands tends to promote the loss of SOC, whilst restoring grasslands tends to have the most positive impact in increasing C accumulation (Smith, 2008).

When it comes to choosing land management practices that promote SOC sequestration, improved grazing – a set of practices that include rotational grazing, irrigation, fertilisation and improved grass species with introduction of legumes – is promoted as to leading to higher soil C sequestration rates. Nevertheless, uncertainty exists in determining the right grazing intensity. Results vary across studies (Maia et al., 2009) and some authors argue that increasing grazing intensity may actually increase SOC by 6-7% on C4[5] grasslands, but decreased SOC by an average 18% in C3-dominated grasslands (McSherry & Ritchie, 2013).

These findings highlight once again the previous understanding we already had of the high impact of context - such as climate, soil type or topography - and other factors - crop-type, temperature and precipitation (Piñeiro et al., 2010) - surrounding the practices in SOC sequestration. Just like in croplands, grasslands results differ very strongly in their response of SOC to grazing, showing that grazer effects on SOC are highly context and region specific.

2.5 Limits to SOC sequestration

Although enhancing soil C is possible through adequate land-use and management practices, the amount of C to be "locked up" is finite, whereby SOC increase ceases as a new equilibrium value is reached. To exemplify: a cropland going through conversion from "conventional" to "no-till" management will show a positive change in soil C content at a rate of increase of SOC which reduces over time, until the soil reaches its new equilibrium, where no more SOC can be sequestered (Powlson et al., 2011). This equilibrium value is the so-called "limit" to SOC sequestration, which is usually reached within 20 to 100 years (Freibauer et al., 2004) after land-use or land management change, which requires to be maintained over time (Figure 2-1). Furthermore, SOC sink capacity also depends on the previous level of SOM, climate, profile characteristics and management (Lal, 2004b).

It is equally important to highlight that this SOC accumulation is reversible, meaning: the change in land use or management which lead to SOC increase must be continued indefinitely (Freibauer et al., 2004b; Powlson et al., 2011), if we aim to lock carbon in the soils.

Lastly, and as previously mentioned, having as climate change mitigation as an end-goal, we must keep in mind that in cases where SOC sequestration may increase, changes in other GHG (such as methane and nitrous dioxide) fluxes may happen and should be quantified so we can understand how exactly are our SOC sequestration practices impacting climate change (Powlson et al., 2011).

[5] According to the authors McSherry & Ritchie (2013) C3 refers to cool season grasses – known to fix CO_2 at cooler temperatures - while C4 refers to warm season grasses – more efficient in fixating CO_2 in high temperatures.

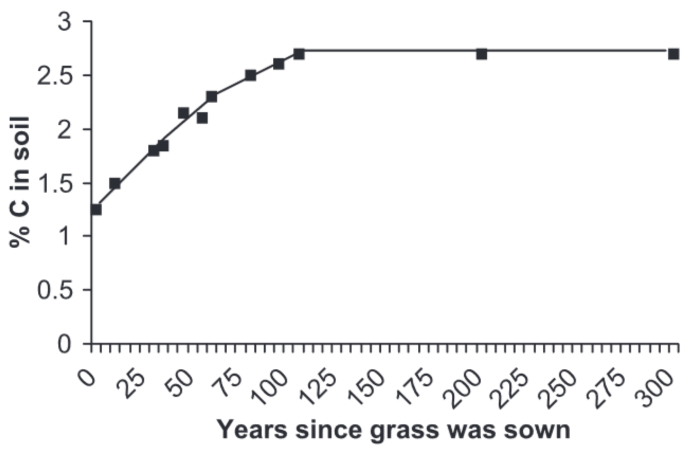


Figure 2-1 - The accumulation of total soil carbon in silty clay loam soils at Rothamsted, UK, when old arable land is sown to permanent grass (Freibauer et al., 2004)

Despite a great deal of research, there currently remains substantial uncertainty in the magnitude of SOC mitigation potentials, adequate management practices and long-term results (Frank et al., 2015; Scharlemann et al., 2014; Schrumpf et al., 2011).

2.6 Estimating, measuring and monitoring SOC

Accurate determination of changes in SOC stocks are a prerequisite for better understanding the role of soils in the global carbon cycle and their capacity to mitigate climate change as well the effects of the application of certain land management practices (Schrumpf et al., 2011).
Monitoring, reporting and verification (MRV) of SOC sequestration as a consequence of management changes in land is a complex process due both to the inherent complexity of the ecosystem processes involved as for other economic, social or legal constraints (Vetter et al., 2022).

IPCC methodology for GHG inventories

Countries under the UNFCCC and the Paris Agreement are required to report anthropogenic emissions by sources and anthropogenic removals by sinks of greenhouse gases. In order to calculate GHG emission flows for the Agriculture, Forestry, and Other Land Use (AFOLU) Sector, the IPCC introduced a three-tiered approach: Tier 1, a more basic method which relies on predefined emission factors, which are soil-type and climate-type specific; Tier 2, similar to Tier 1, but relies on country and region-specific emission factors, and lastly, Tier 3, where higher order methods such as detailed monitoring networks and/or process-based models driven by detailed region specific data are used (Vetter et al., 2022). Higher tiered levels require extensive data collection efforts (such as detailed measurements resulting from field sampling), the use of sophisticated or improved models which factor a wide range of data (such as environmental, economic, or technological specifics) and application of continuous verification to ensure data accuracy and reliability.

Details of the IPCC Guidelines for GHG Inventories are more thoroughly explored in the Methodology section since they were used to estimate SOC potentials in Portuguese Cropland and Grassland.

Modelling SOC

Models are extremely useful because they can capture and mimic real-world systems and generate outputs over time. They can be used efficiently to model environmental systems and results can contribute to a better understanding of complex phenomena, such as global climatic changes, biodiversity, deforestation, risk prevention and land planning at the local level, etc, (Paegelow & Camacho Olmedo, 2008) so it is no surprise that simulations can be used to emulate SOC dynamics and estimate SOC sequestration potentials.

SOC models enable estimation of soil carbon stocks and soils' carbon sequestration (or loss) potential over time as well as other climate and soil variables (Liu et al., 2011; Rehman et al., 2023). Process-based SOC models, which follow IPCC's Tier 3 approach, allow for the simulation of the mechanistic effect of anthropogenic (land management) and natural (climate and soil) drivers, with the possibility to assess the effect of alternative scenarios (Lugato et al., 2014). The CENTURY Model or RothC are process-based models that integrate crop growth routines and the effect of the main management practices in the agricultural fields such as tillage, grazing, irrigation, fertilisation, using a monthly time step (Stockmann et al., 2013). RothC is widely used to assess the effects of future climate change on the SOC dynamics (Afzali et al., 2019). Organism-oriented models are another type of SOC models. These are not so popularly used to model SOC dynamics, yet they provide understanding of C and N flow through food webs and explore the role of soil biota in C and N mobilisation (Stockmann et al., 2013).

In the past decade, machine learning has gained traction across a variety of disciplines, due to its ability to analyse and learn from vast amounts of data and generate outputs and insights in ways that mimic the human brain exertion of experience but at faster rates (Zhou, 2021). As computation power increases, machine learning may well become the preferred approach to analysing extensive amounts of data and deploying estimations for soil related properties.

Although showing promising results, the modelling of SOC still comprises a lot of uncertainty (Scharlemann et al., 2014), with substantial discrepancies in modelled estimations of global SOC stocks and sequestration potentials.

Field measurements

Direct measurement of SOC stock changes relies on physical sampling and further soil C content measurements and of other soil properties such as organic carbon (OC) concentrations, bulk density (BD), stone content, as well as soil depth (Schrumpf et al., 2011). This approach requires appropriate study designs and sampling protocols as well as a large sampling number in order to reduce potential sources of error (Schrumpf et al., 2011; Smith et al., 2020). Field measurements - including periodic on site measurements or long-term monitoring over time - are time and labour

consuming with an elevated cost demand in all stages (from collection to processing, measurement and storage of soil samples) (Vetter et al., 2022).
The IPCC recommends measurements be done to a depth of at least 30 cm. For certain soils and in order to measure the effect of specific improved management practices, it may be required to sample up to 100 cm in depth (FAO, 2019) in order to avoid biased results regarding SOC content (Baker et al., 2007; Luo et al., 2010).
Beyond the resource magnitude both in terms of labour, time as well as cost, in-situ measurements are also invasive, disturbing the cropland area in which the sample extraction takes place. They are, nevertheless, the current most direct form of SOC measurement offering the most accurate and "realistic" information regarding site specific carbon content and are essential inputs to models.

European level soil monitoring – LUCAS

The Land Use/Cover Area frame statistical Survey (LUCAS) Database is a result of a three-yearly basis survey carried out by EUROSTAT since 2006. It focuses on the state and the dynamics of changes in land use and cover in the European Union and is carried out in-situ, resulting in a registration of many observations are throughout the EU. Since 2012, all 27 EU countries have been covered and over 270,000 points have been analysed on different land cover types (cropland, grassland, forest, built-up areas, transport network, etc.). It represents the first attempt to build a consistent spatial database of the soil cover across the EU based on standard sampling and analytical procedures.
In 2009, the sampling of the main properties of topsoil in 23 Member States of the European Union (EU) took place, resulting in a total of 20,000 sampled points around Europe, at a 20 cm soil depth. In 2012, the soil survey was extended to Romania and Bulgaria. In 2015, the LUCAS survey was carried out in all EU-28 Member States; in the countries sampled in 2009 and 2012, 90% of the locations were maintained while the remaining 10% of points were substituted by new sampling locations. Finally the LUCAS 2018 Soil Module dataset contains data for 18,984 locations.

National level soil monitoring

The INFOSOLO database is the first effort to develop a soil information system in Portugal that is suitable to compile soil data produced in the country and support farmers and government entities in the process of decision making, contributing to improving knowledge regarding soil status, like other global initiatives such as the Global Soil Partnership, or organizations like the ISRIC (World Soil Information) in the common effort to improve reliability of soil data towards a better assessment of suitable land management practices.
The need to develop a national database like INFOSOLO arose from the realization that, although many initiatives existed, the databases provided insufficient data in many regions of the world, including Portugal. For example, the WISE dataset contains 10,253 soil profiles collected around the world, but only 10 were from Portugal. And, even though the LUCAS database covers soil

data in 270,000 points around Europe, only 465 points are in Portugal which, according to authors and INFOSOLO database developers T.B. Ramos et al. is insufficient. And, despite a significant investment on mapping soils in different regions of Portugal in the last decades led by public institutions, the data has remained scattered, almost ‘trapped’ inside the institutions’ databases that gathered it.

INFOSOLO is a georeferenced database that currently gathers information of 3461 soil profiles across Portugal, which resulted from sampling campaigns in the period from 1966 to 2014. This database includes identification of the soil profiles (such as corresponding coordinates, elevation, year of sampling, WRB Reference Soil Groups, to name a few), properties of the soil (information of coarse elements, clay, bulk density, organic carbon, nitrogen, phosphorus, and others) and methods used for analytical data characterization of the soil profile (Ramos et al., 2017).

All in all, INFOSOLO presents itself as an important step towards the development of a reliable common soil information system in Portugal. Still, there is space for greater action towards soil quality monitoring which extends over time. An European example of an ongoing quality monitoring network is the French RMQS network which is based on the monitoring of 2240 sites spread evenly over the French territory, of which soil samples are taken every 10 to 15 years, allowing for the accurate reassessment of soil carbon stocks and the mapping of soil microbial richness and diversity and changes over the years (Jolivet et al., 2022).

Spectral methods / Remote sensing

In addition to *in-situ* measurements at field and farm level, remote sensing can extensively help validate SOC data as well as monitor land-use and vegetation change. Usually installed on satellites that orbit the Earth, these sensors rely on spectral methods which quantify the electromagnetic energy reflected by the bonds in the SOC molecules (O-H, N-H, C-H). Then, and through the use of a statistical model based on a soil type spectral library, a quantitative and qualitative analysis of SOC can be obtained (Smith et al., 2020; Vetter et al., 2022).

Remote Sensing, although cost and time efficient, provides very limited information regarding changes in SOC stocks, since its measuring capacity only goes as deep as 1 cm of depth, which is not sufficient to fully evaluate whether SOC accumulation is taking place. Nevertheless, it is a useful tool which can and should be used to complement in-situ measurements.

2.7 Unknowns, uncertainties, and the pathway forward

The limited availability of globally equally spread-out data on soil properties, degradation status, carbon content/carbon sequestration potentials and established land management and land-use practices is a commonly mentioned obstacle towards the development of reliable science which contributes to correctly informing policy makers and farmland managers on the ideal methods towards soil C sequestration. Filling such knowledge gap requires that efforts are put into researching at a local level to improve reliability of data through adequate measuring and verification procedures which overall contribute to the identification of the challenges being faced towards soil carbon sequestration: What practices may work better in certain sites? What are some of the trade-offs that should be considered? What are some of the (biophysical, economic) limits? These are some of the questions which require answering if we aim to enhance soil carbon sequestration as well as global mitigation efforts.

Our work in this thesis aims to contribute to reducing the knowledge-gap in soil organic carbon sequestration in Portugal, understand whether the application of the Tier 1 methodology to determine SOC stocks and sequestration potentials is adequate for the Portuguese scenario and develop a basis on which further work may be built upon.

3 Methodology

3.1 Study Area

Study area

Mainland Portugal is located approximately between the latitudes of 37ºN and 42ºN and the longitudes of 9.5ºW and 6,5ºW, in the south-west extremity of Europe and it has an area of approximately 9.2 Mha.

Climate

The Portuguese Institute for Sea and Atmosphere (IPMA) provides weather data series of observations which date back to 1865 and is responsible for assessing the climate in Portugal and providing the World Meteorological Organization (WMO) climatological normals. The latest available climatological normals (1971-2000) allow for the classification of different climates for Portugal Mainland, which, according to the latest Koppen classification revision (1936), classifies Portugal Mainland as mostly temperate continental climate (Type C) with a small arid region (Type B). The interior regions of the Douro Valley and Alentejo and Algarve areas are classified as Csa (temperate climate with warm and dry summer), while in almost all regions of the northern mountain system Montejunto-Estrela and some regions of the west coast of Alentejo and Algarve are classified as Csb (temperate climate with dry and mild summer). A small region of Alentejo in the district of Beja is classified as BSK, arid, cold steppe climate of mid-latitude (*IPMA - Clima Normais*).

Rainfall prevails during the winter which may cause waterlogging, and its scarcity during the spring induces drought stress in some regions of Portugal (Carvalho & Lourenço, 2014). This drought stress, and particularly, the extreme droughts occurring in most areas to the south of Tejo have been a main driver of yield gaps especially in the production of cerals (INE, 2023).

Portugal’s agricultural land

The distribution of agricultural land uses in Portugal is shown in Figure 3-1. In 2019, permanent pastures consisted mostly of poor pastures (68%) followed by improved permanent sown and spontaneous pastures (28%). Permanent crops were dominated by olive groves (44%), followed by walnut, hazelnut, and almond nut trees (27%) and vineyards (20%). As for annual crops, forages – crops for animal feeding - were predominant (49%), followed by cereals (26%) (INE, I.P., 2021).

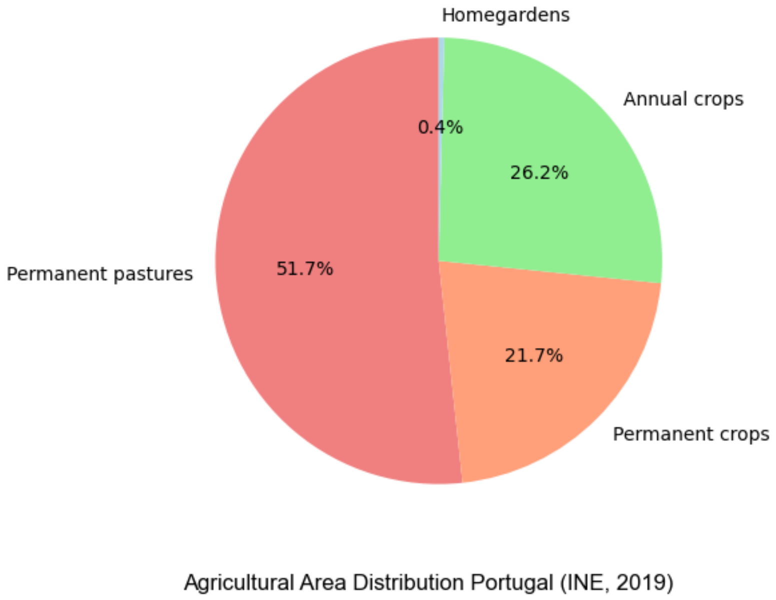


Figure 3-1 - Agricultural area distribution in Portugal (INE, 2019)

3.2 Data collection and processing

LUCAS database

The LUCAS database consists of a master grid of 2x2 km which includes 1.000.000 points covering the EU-27 territory. Each of these points (POINT_ID), is classified into a series of attributes that include information on coordinates, elevation and slope (European Commission, 2013). This grid provides 22,139 georeferenced points covering the entirety of Mainland Portugal. This grid used as the starting point for the development of our database.

From these 22,139 points, a subsample was used to collect and analyse soil samples (LUCAS soil survey) in the years of 2009 (207 points in cropland and grassland), 2015 (190 points) and 2018 (181 points). The information collected included various parameters. For this work we used: coarse particle content and organic carbon concentration at a 20 cm depth. In the year of 2018, the sampling was more detailed for 65 cropland and grassland sites, and information was also collected for: organic carbon concentration at 20-30 cm depth, and bulk density at depths of 0-10 cm, 0-20 cm, 10-20 cm and 20-30 cm.

Soil classification data

LUCAS does not provide information on soil type for each point. In the absence of a National official soil map, we used the soil classification data for Portugal Mainland extracted from the Soil Atlas of Europe. The atlas is the result of a 20-year collective effort of a series of field observations by more than 40 national soil surveys and soil science institutions cooperating across Europe. Europe's 32 major soil groups are classified according to the WRB (World Reference Base for Soil Resources) soil classification system. Additionally, there are 120 unique qualifiers that are defined to describe specific soil characteristics, following the Food and Agriculture Organization (FAO)-85 classification system (A. Jones & European Comission, 2005).

Meteorological data

Maps of temperature, precipitation, and evapotranspiration in raster format were downloaded from Portal do Clima (http://portaldoclima.pt) provided by IPMA. This data is a result of both observations and models, for a reference climate normal of 1971-2000.

Land-use and land cover

Data on land-use in Mainland Portugal was obtained from COS (Carta de Ocupação de Solos), produced by DGT (Direção Geral do Território). It provides information regarding land-use and land-cover in Portugal and available to download from SNIG (Sistema Nacional de Informação Geográfica) (https://snig.dgterritorio.gov.pt/). Maps were retrieved for the years of 2010 (COS2010v2.0), 2015 (COS2015v2.0), and 2018 (COS2018v2.0). These include 83 different land occupation classes which, for simplification purposes, where reduced into 19 different classes, described in Table 3-1.

Table 3-1 - Simplified COS land-use classification (https://snig.dgterritorio.gov.pt/, adapted)

Descriptor	LU1	LU2	Description
CL	Cropland	CL1	Rainfed Annual Crops
		CL2	Irrigated Annual Crops
		CL3	Rice Paddies
		CL4	Vineyards
		CL5	Olive Groves
		CL6	Other Permanent Crops
FL	Forest land	FL1	Maritime Pine
		FL2	Stone Pine
		FL3	Other
		FL4	Eucalyptus
		FL5	Cork Oak
		FL6	Holm Oak
		FL7	Other Oaks
		FL8	Other Hardwood
GL	Grassland	GL1	Pastures
		GL2	Scrubland
ST	Settlements	ST1	Settlements
WT	Wetlands	WT1	Inland Waters
		WT2	Wetlands

For our assessment, we were particularly interested in cropland and grassland land-uses in the years of 2010, 2015 and 2018. Table 3-2 shows the shares of land used for grassland and cropland.

Table 3-2 - Land-use, COS (2010, 2015, 2018), Cropland and Grassland (%)

	Shares (%), Cropland and Grassland Combined		
Land-Use (COS)	**2010**	**2015**	**2018**
Rainfed Annual Crops (CL1)	37%	36%	35%
Irrigated Annual Crops (CL2)	15%	15%	15%
Rice Paddies (CL3)	1%	1%	1%
Vineyards (CL4)	17%	17%	18%
Olive Groves (CL5)	3%	4%	4%
Other Permanent Crops (CL6)	3%	4%	4%
Pastures (GL1)	23%	23%	22%

Land-uses for the year of 2018, for cropland (CL) and grassland (GL) types across Portugal Mainland are represented in Figure 3-2, for a total of 7,184 LUCAS grid points.

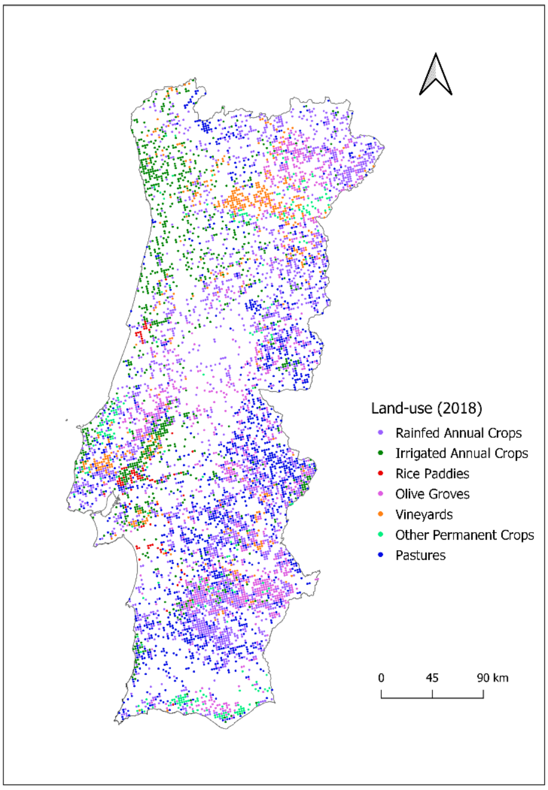


Figure 3-2 - Land-use (2018) cropland and grassland, n = 7,184

Mainland Portugal sub-regions (NUTS 3)

A shapefile for the Portuguese administrative regions is available to download at dados.gov.pt. The file provides the official limits at different Nomenclature of Territorial Units for Statistics (NUTS) levels (NUTS 1, NUTS 2 and NUTS 3). We were only interested in the sub-region levels (NUTS 3) for our assessment, which may be viewed in Figure A-2 of the Appendix.

Processing

All the data was retrieved in either ERSI shapefiles (.shp) or raster files which could be further processed on QGIS 3.0 software, an open-source geographic information system application that supports viewing, editing, processing, and analysis of geospatial data (https://www.qgis.org/en/site/). The different layers were processed with QGIS, and data was compiled using QGIS's processing providers "Join Attributes by Location" and the "Extract Multi Values To Points tool", for raster files. The result is the original LUCAS 2x2 km grid shapefile with 22,139 georeferenced points (POINT_ID), described by a set of fields, represented in Table 3-3.

Table 3-3 - Database descriptors

Field Name	Description	Data Source	Unit
POINT_ID	LUCAS Georeferenced Point ID	LUCAS	-
coarse_09	Coarse (%) 2009	LUCAS	%
coarse_15	Coarse (%) 2015	LUCAS	%
coarse_18	Coarse (%) 2018	LUCAS	%
OC_09	Organic Carbon 2009 at 20 cm depth	LUCAS	g/kg
OC_15	Organic Carbon 2015 at 20 cm depth	LUCAS	g/kg
OC_18	Organic Carbon 2018 at 20 cm depth	LUCAS	g/kg
OC_2030cm_	Organic Carbon 2018 at 20-30 cm depth	LUCAS	g/kg
BD_0010cm_	Bulk Density 2018 at 0-10 cm depth	LUCAS	t/m^3
BD_1020cm_	Bulk Density 2018 at 10-20 cm depth	LUCAS	t/m^3
BD_2030cm_	Bulk Density 2018 at 20-30 cm depth	LUCAS	t/m^3
BD_0020cm_	Bulk Density 2018 at 0-20 cm depth	LUCAS	t/m^3
NUTS3	NUTS-III: Subregions Mainland Portugal	dados.gov.pt	-
PPAnoTot	Total Annual Precipitation	IPMA	mm/y
TAnMed	Annual Average Temperature	IPMA	ºC
TAnMedN<0	Days of Frost	IPMA	days/y
EV0_mp_sm	Evapotranspiration	IPMA	mm/y
EV0_ic_sm	Evapotranspiration	IPMA	mm/y
EV0_ic_kn	Evapotranspiration	IPMA	mm/y
EV0_ic_dm	Evapotranspiration	IPMA	mm/y
EV0_en_en	Evapotranspiration	IPMA	mm/y
EV0_cn_sm	Evapotranspiration	IPMA	mm/y
LU2_10	Land-use 2010	COS/DGT	-
LU2_15	Land-use 2015	COS/DGT	-
LU2_18	Land-use 2018	COS/DGT	-
Soil_Class	Soil Classification FAO-85	EU Soil Atlas	-

3.3 IPCC Tier 1 methodology

General overview of the IPCC Guidelines

The IPCC Guidelines provide a framework for the development of a National GHG Inventory. It is organised in five different volumes: General Guidance; Energy; Industrial Processes and Product Use; Agriculture, Forestry, and Other Land Use (AFOLU); and Waste. These guidelines were first introduced in 1994 to promote consistency between countries' emission inventories and allow comparison between estimations. Since then, these guidelines have suffered improvements to reflect the most recent scientific understanding and techniques. The latest version of IPCC's National GHG Inventory was released in 2020, "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories".

Volume 4: "Agriculture, Forestry and Other Land Use", was used in this work to determine cropland and grassland soil carbon stocks and carbon stock changes, notably SOC_{REF}, estimate $SOC_{Baseline}$ and SOC stock changes over a period of twenty years. The analysis was concentrated on the contribution of soils and so the methodologies for estimating emissions and removals from other pools were not considered. Volume 4 is divided in 12 chapters. References for this work came mostly from Chapter 1 (Introduction), Chapter 2 (Generic Methodologies Applicable to Multiple Land-Use Categories), Chapter 5 (Cropland) and Chapter 6 (Grassland).

As previously explained in the State of the Art section of this dissertation, IPCC's Inventory Framework for AFOLU provides three different Tier Levels for assessing carbon stock changes and GHG emissions. Tier 1 is the simplest method and requires the least local information to be applied. Tier 2 and Tier 3 are referred as higher tier methods which demand higher complexity and data inputs, being generally considered as more accurate and even recommended when the category going through inventory is a main one. However, higher tiered levels require extensive data collected to reflect National circumstances. Such data for soils is not available in Portugal and the application of a Tier 1 method is the most suitable in these conditions.

The Tier 1 approach relies on country specific data such as climate classification and soil classification and follows the assumptions that i) SOC is at an equilibrium, ii) SOC changes occur linearly for a period of 20 years (Figure 3-3). Guidelines are also provided on how to classify soils and climate, through a series of steps which should contribute to guarantee robustness and comparability of the inventory process between countries and regions.

The IPCC considers six land-use categories:

- Forest Land: natural forest, managed forest, plantations, agroforestry systems.
- Cropland: cereals, pulses, fruit crops and other annual and permanent crops.
- Grassland: pastures used for livestock grazing.
- Wetlands: marshes, swamps, lakes, water reservoirs and other areas with standing water.
- Settlements: urban areas.
- Other Land: sand dunes, rocky areas, deserts

SOC is calculated at equilibrium, and is based on a SOC reference stock, $\mathrm{SOC_{REF}}$, and a set of Stock Change Factors (SCFs) which account for the effects of land-use ($\mathrm{F_{LU_{c,i}}}$), land management ($\mathrm{F_{MG_{c,i}}}$) and input type ($\mathrm{F_{I_{c,i}}}$) on SOC, described by

$$SOC = \sum\nolimits_{c,s,i}^{i} \left(SOC_{REF\,c,s} \times F_{LU_{c,i}} \times F_{MG_{c,i}} \times F_{I_{c,i}} \right), \qquad (1)$$

where SOC is the organic carbon at equilibrium in the soils at a 30 cm depth (tC ha^{-1}); $SOC_{REF\,c,s}$ (tC ha^{-1}) and the set of SCFs (dimensionless) values are provided by the IPCC for each "c", "s" and "i" which represent, respectively, the climate zones, soil types and a set of management characteristics such as tillage or input.

To calculate annual stock changes, ΔC, in soils for cropland and grassland land-use types, we apply the 'Stock Difference Method' to calculate the carbon stock change in a given pool as an annual average difference between estimates at two points in time,

$$\Delta C = \frac{SOC_{final} - SOC_{Baseline}}{D}, \qquad (2)$$

where ΔC is the annual change in organic carbon stocks in soils, in tC ha^{-1} y^{-1}, SOC_{final} is the soil organic carbon at a depth of 0-30 cm (tC ha^{-1}) after D years of application land-use conversion or change in land management practice, at equilibrium, $SOC_{Baseline}$ is the initial soil organic carbon at a depth of 0-30 cm (tC ha^{-1}), at equilibrium, and D is the period of application of the new land-use conversion or change in land management which corresponds to 20 years.

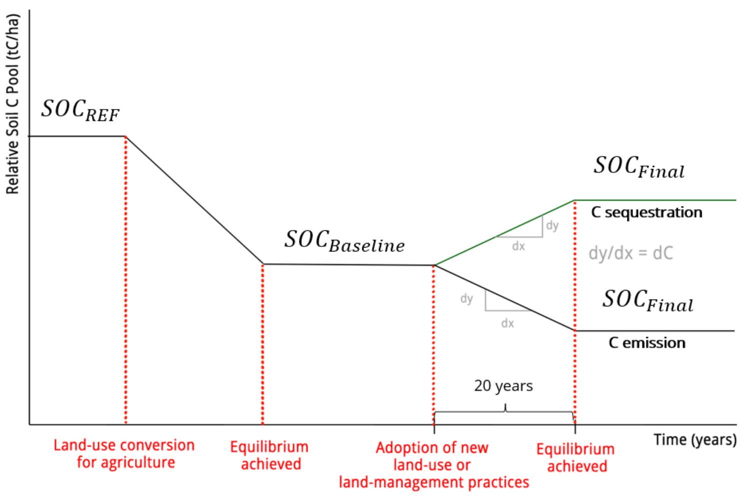


Figure 3-3 – Assumptions of SOC dynamics of the IPCC Tier 1 Methodology. dy/dx = dC, annual stock change over a 20-year period

3.4 Application of the Tier 1 methodology

Climate classification

The climate assessment was carried out following IPCC's Classification scheme for default climate regions. The reduced scheme relevant to our assessment is represented in Figure 3-4.
This classification scheme is based on the gridded Climate Research Unit (CRU) Time Series (TS) monthly climate data for the period from 1985 to 2015, and follows the methodology defined by Haris et al. (2014). The IPCC default climate zones are: Tropical Montane, Tropical Wet, Tropical Moist, Tropical Dry, Warm Temperate Moist, Warm Temperate Dry, Cool Temperate Moist, Cool Temperate Dry, Boreal Moist, Boreal Dry, Polar Moist, Polar Dry. Our assessment resulted in three climate zones for Mainland Portugal: Warm Temperate Dry, Warm Temperate Moist and Cool Temperate Moist.
The climate assessment requires data on:

- Mean Annual Temperature (MAT) in ºC
- Mean Annual Precipitation (MAP), in mm year $^{-1}$
- Potential Evapotranspiration (PET), in mm year $^{-1}$
- Days of frost year $^{-1}$

This data was obtained from IPMA, whereby the 'mean annual temperature' (MAT) corresponds to IPMA obtained 'TAnMed' and 'mean annual precipitation' (MAP) to IPMA's data on annual precipitation, 'PPAnoTot', previously represented in Table 3-3.
While data for temperatures and precipitation is data based on observations, data on potential evapotranspiration per day (PET) is provided by IPMA as estimates from 5 different models 'EV0_mp_sm', 'EV0_ic_sm', 'EV0_ic_kn', 'EV0_ic_dm', 'EV0_en_en', 'EV0_cn_sm'. We used the average of the different models as an approximation of the "real" PET values for each georeferenced point, as described by

$$PET_i = \frac{EV0_{ic_{sm}} + EV0_{ic_{kn}} + EV0_{ic_{dm}} + EV0_{en_{en}} + EV0_{cn_{sm}}}{5} \times 365 \qquad (3)$$

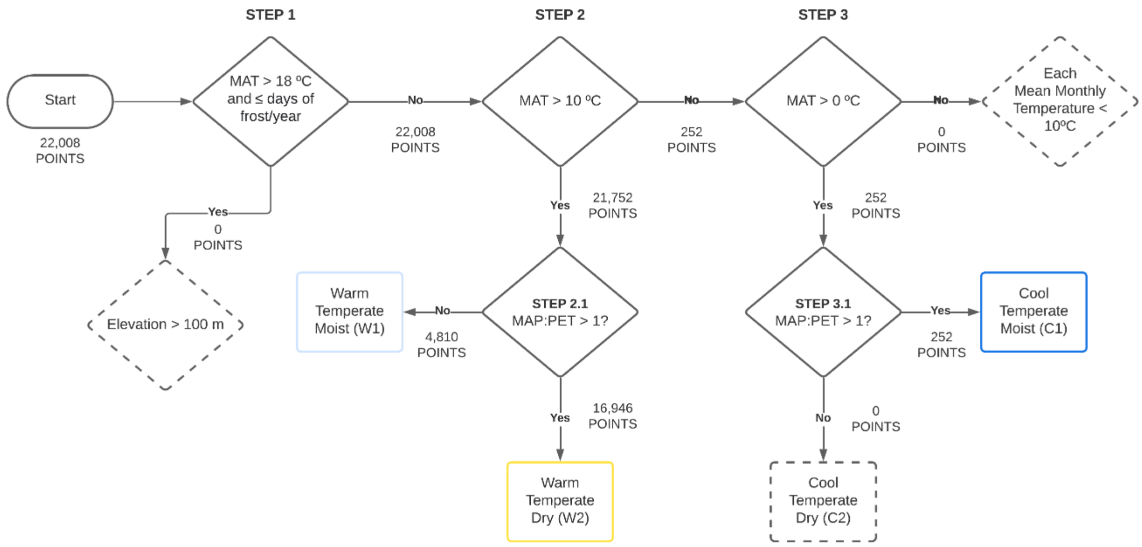
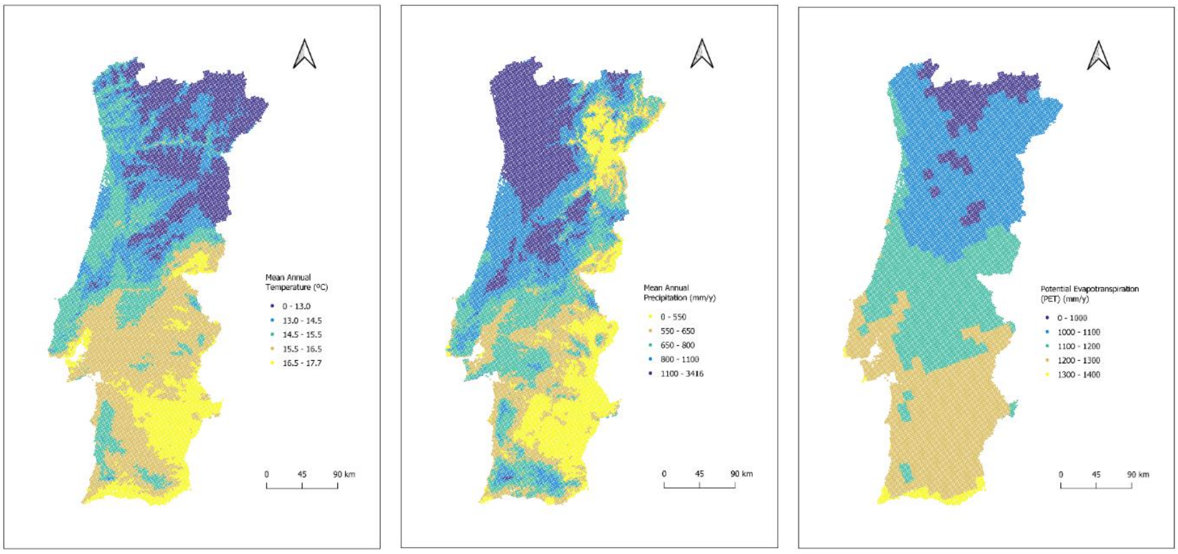


Figure 3-4 - Climate classification decision tree. Adapted from IPCC (2019)

From the total of 22,139 unique georeferenced points in Portugal Mainland, a total of 84 points had missing evapotranspiration values, while 47 had missing temperature values. These points were mostly located on the Portuguese-Spanish border and most likely result from differences in country border used in the different input files. For these points, we applied a 'Nearest neighbour analysis,' a tool that enables us to fill data gaps for georeferenced points by identifying the closest classified neighbour.

Table 3-3 – IPCC climate classification after gap-filling

STEPS			**POINT_ID (n)**	**IPCC Climate Classification**
Step 1	**MAT > 18ºC and < 7 days of frost / year?**		0	
Step 2	**MAT > 10ºC**		**22139**	
	Step 2.1	MAP/PET > 1	4834	Warm Temperate Moist (W1)
		MAP/PET < 1	17049	Warm Temperate Dry (W2)
Step 3	**0ºC < MAT < 10ºC**		**256**	
	Step 3.1	MAP/PET > 1	256	Cool Temperate Moist (C1)



a) *b)* *c)*

Figure 3-5 – Input data climate classification: mean annual temperature (ºC): a), mean annual precipitation (mm): b), potential evapotranspiration (mm y^{-1}): c), n=22,139

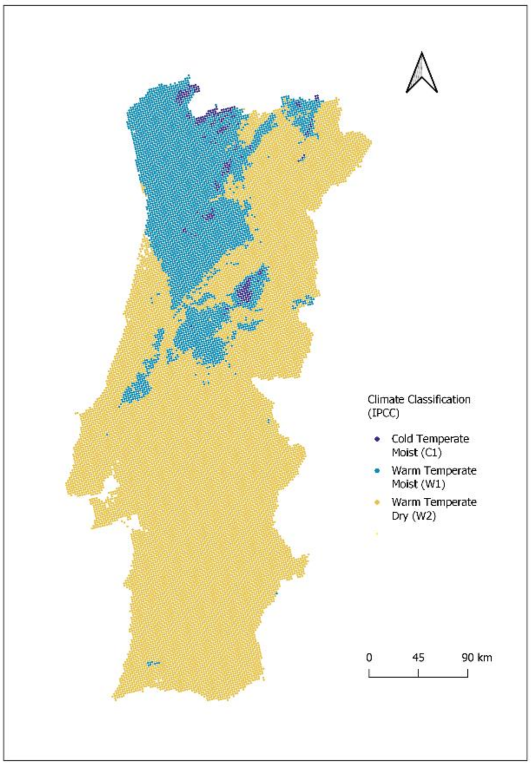


Figure 3-6 - IPCC climate classification, n=22,139

As we may observe Figure 3-6, Warm Temperate Dry climate dominates (77% of the country), followed by Warm Temperate Moist (22%) and Cool Temperate Moist (1%).

Soil classification

As previously mentioned, the soil classification data for Mainland Portugal is based on the legend of the FAO-85 Classification. This classification was extracted from the Soil Atlas of Europe, 2005 (see Figure A-1 of the Appendix) and then converted to IPCC Soil Classification following the correspondence Table 3-4 as suggested by (Batjes, 2009)[6].

Table 3-4 - FAO-85 (FAO85LV3/FAO85LV3_t) to IPCC soil classification (Soil_IPCC) correspondence table (Batjes, 2009)

FAO85LV3	FAO85LV3_t	Soil_IPCC	Full Name
Ag	Gleyic Acrisols	LAC	Low Activity Clay
Bc	Chromic Cambisols	HAC	High Activity Clay
Bcc	Calcaro-chromic Cambisols	HAC	High Activity Clay
Bd	Dystric Cambisols	HAC	High Activity Clay
Be	Eutric Cambisols	HAC	High Activity Clay
Bh	Humic Cambisols	HAC	High Activity Clay
Bk	Calcic Cambisols	HAC	High Activity Clay
Je	Eutric Fluvisols	HAC	High Activity Clay
Lcr	Rhodo-chromic Luvisols	HAC	High Activity Clay
Lf	Ferro Luvisols	LAC	Low Activity Clay
Lga	Albo-gleyic Luvisols	HAC	High Activity Clay
Lkc	Chromo-Calcic Luvisols	HAC	High Activity Clay
Lo	Orthic Luvisols	HAC	High Activity Clay
Lv	Vertic Luvisols	HAC	High Activity Clay
Po	Orthic Podzols	POD	Podzol
Qc	Cambic Arenosols	SAN	Sandy
Qh	Haplic Arenosols	SAN	Sandy
Rd	Dystric Regosols	HAC	High Activity Clay
Re	Eutric Regosols	HAC	High Activity Clay
U	Ranker	HAC	High Activity Clay
Vc	Chromic Vertisols	HAC	High Activity Clay
Vp	Pellic Vertisols	HAC	High Activity Clay
We	Eutric Planosols	HAC	High Activity Clay
Zg	Gleyic Solonchaks	HAC	High Activity Clay

The resulting IPCC Soil Classification for the 22,139 points is shown in Figure 3-7. The prevalence of each soil type in Mainland Portugal is shown in Table 3-5.

[6] Shown only for Soil Types present in Mainland Portugal

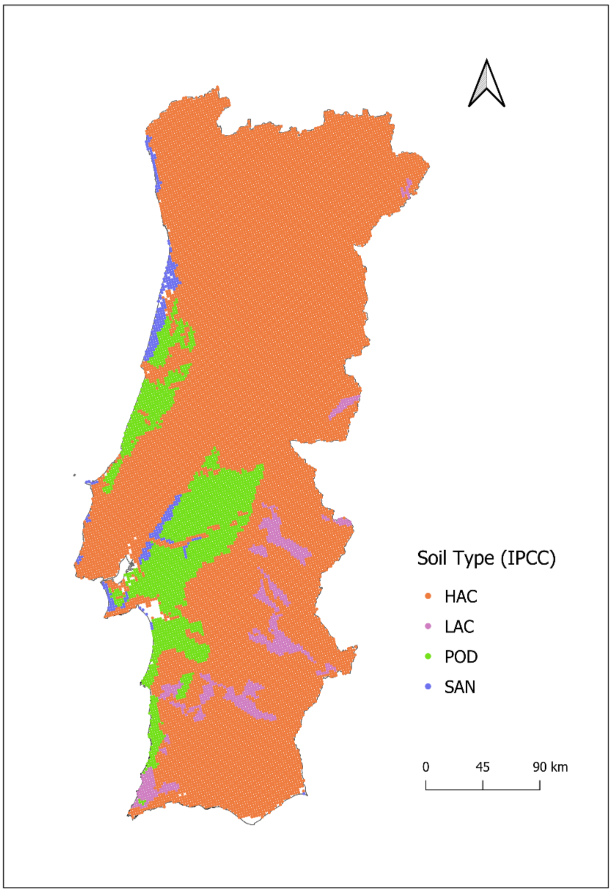


Figure 3-7 - IPCC soil classification, n=22,139

HAC – High Activity Clay, LAC – Low Activity Clay, POD – Podzols, SAN – Sandy

Table 3-5 – Soil classification according to IPCC and respective shares (%)

Soil Classification (IPCC)	POINT_ID (n)	Share (%)
High Activity Clay (HAC)	18551	84%
Low Activity Clay (LAC)	839	4%
Podzol (POD)	2436	11%
Sandy (SAN)	313	1%
Total	**22139**	**100**

Carbon accounting

SOC stocks at “no-use/management” situation (SOC_{REF})

Soil organic carbon reference stocks are a set of estimates of SOC stocks in mineral soil, at a 30 cm depth, dependent on climate and soil type combination. These represent “aspirational” SOC stock values, i.e. carbon stocks of undisturbed soils.

SOC_{REF} values were obtained for the 22,139 LUCAS grid points, according to each point's climate and soil type. SOC Reference stocks mean values (SOC_{REF}), confidence intervals (u), and standard deviation (σ), which result from each climate and soil types combination are provided in Table 3-6, adapted from Table 2.3 of IPCC Guidelines 2019 Vol. 4 Ch. 2 (IPCC, 2019).

Table 3-6 - IPCC SOC_{REF} (tC ha^{-1}) at 0-30 cm depth, confidence intervals, (u, %), standard deviation (σ), according to climate and soil combination, adapted from Table 2.3 of IPCC Guidelines 2019 Ch.2 (2019)

		IPCC Climate		
IPCC Soil	**IPCC Values**	**Cold Temperate Moist (C1)**	**Warm Temperate Dry (W2)**	**Warm Temperate Moist (W1)**
High Activity Clay (HAC)	**SOC_{REF}** (tC ha^{-1})	**81**	**24**	**64**
	u (%)	±5%	±5%	±5%
	σ	±2.03	±0.60	±1.60
Low Activity Clay (LAC)	**SOC_{REF}** (tC ha^{-1})	**76**	**19**	**55**
	u (%)	±51%	±16%	±8%
	σ	±19.38	±1.52	±2.20
Sandy (SAN)	**SOC_{REF}** (tC ha^{-1})	**51**	**10**	**36**
	u (%)	±13%	±50%	±23%
	σ	±3.33	±2.50	±4.14
Podzols (POD)	**SOC_{REF}** (tC ha^{-1})	**128**	**51.5**[7]	**143**
	u (%)	±14%	-	±30%
	σ	±8.96	±7.71	±21.45

U are confidence intervals at 95%, assumed to be derived from a normal distribution (IPCC, 2019). According to the "95-rule", for normal distributions, approximately 95% of the data falls within two standard deviations of the mean (μ ± 2σ). This allowed us to estimate the standard deviation (σ) of each soil/climate pair, which was then instrumental in the execution of Monte Carlo Simulations to estimate variability.

Computing $SOC_{Baseline}$ stocks for grassland and cropland

To compute the current SOC stocks of Grassland and Cropland managed points ($SOC_{Baseline}$), we used the latest to COS's land-use data (2018), and a series of 'default' management conditions (management and input) were set for each land-use type. These correspond to the set of conditions before the application of new land management or land-use.

[7] W2/POD SOC_{REF} mean and confidence interval (u) values were not provided by the IPCC since it is not considered a *common* climate/soil combination. This combination occurs in Portugal, hence SOC_{REF} and σ were estimated to continue our assessment. The equations followed to obtain these values are shown in section 0 of the Appendix.

Table 3-7 – IPCC land-use and land management conditions to characterize SCFs (land-use (F_{LU}), land management (F_{MG}) and input type (F_I)) at baseline, per land-use type according to COS 2018

	IPCC land-use and land management conditions		
Land Use Type (COS, 2018)	**F_{LU} Land-Use**	**F_{MG} Management**	**F_I Input**
Rainfed Annual Crops (CL1)	Long term cultivated	Full tillage	Medium
Irrigated Annual Crops (CL2)	Long term cultivated	Full tillage	High without manure
Rice Paddies (CL3)	Paddy Rice	NA[8]	NA[8]
Vineyards (CL4)	Tree Crop	Reduced tillage	Low
Olive Groves (CL4)	Tree Crop	Reduced tillage	Medium
Other Permanent Crops (CL6)	Tree Crop	Reduced tillage	Medium
Pastures (GL1)	All	High Intensity Grazing	Medium

These land-use and land management conditions define the Stock Change Factors (SCFs) for each climate type. These values are available in Table B-1 and Table B-2, which will then be used as inputs to determine the $SOC_{Baseline}$ of each site with Equation (1).
As specific data on land management practices at a local/farm scale is not available, the set of management conditions proposed for each land-use type greatly simplify the diversified reality of land management in agricultural sites around Portugal.

Computing SOC stocks with alternative land-use or land management alternatives and Annual SOC Changes in soils

We now aim to estimate the effects of application of different management and crop transitions on SOC stocks, over a period of 20 years, to represent the potentiality of specific changes in land management and land-use. In this thesis we explored the following changes: transition from full till to to no-till in annual crops (T1); conversion from rainfed to irrigated annual crops (T2); conversion of annual crops to perennial crops (T3); and grassland improvement (T4). The management conditions for each land-use type and moment in time (baseline or final) are represented in Table 3-7.

[8] 'NA' denotes 'Not Applicable', where factor values constitute defined reference values, and the uncertainties are reflected in the reference C stocks and stock change factors for land use (IPCC, 2019).

Table 3-7 – IPCC land-use and land management conditions to characterize SCFs (land-use (F_{LU}), land management (F_{MG}) and input type (F_I)) per 'baseline'' and 'final' land-use type

				IPCC land-use and land management conditions		
Transition			**Land Use Type**	**F_{LU} Land Use**	**F_{MG} Management**	**F_I Input**
T1		**Full Till** Baseline	Rainfed Annual Crops (CL1), Irrigated Annual Crops (CL2)	Long term cultivated	Full tillage	Medium, High (without manure)
		No-Till Final			No-till	High (without manure)
T2		**Rainfed** Baseline	Rainfed Annual Crops (CL1)	Long term cultivated	Full tillage	Medium
		Irrigated Final	Irrigated Annual Crops (CL2)			High (without manure)
T3	**T3A**	**Rainfed Annual Crops** Baseline	Rainfed Annual Crops (CL1)	Long term cultivated	Full tillage	Medium
		Irrigated Intensive Permanent Crops Final	Olive Groves (CL6), Other Permanent Crops (CL7)	Tree crop	Reduced tillage	High (without manure)
	T3B	**Irrigated Annual Crops** Baseline	Irrigated Annual Crops (CL2)	Long term cultivated	Full tillage	High (without manure)
		Irrigated Intensive Permanent Crops Final	Olive Groves (CL6), Other Permanent Crops (CL7)	Tree crop	Reduced tillage	High (without manure)
T4		**Natural Poor Grasslands** Baseline	Pastures (GL1)	All	High intensity grazing	Medium
		Improved Grasslands Final		All	Improved	High

Correspondent SCF values $F_{LU_{c,s,i}}, F_{MG_{c,s,i}}, F_{I_{c,s,i}}$ (mean values), confidence intervals (as 'Error') per climate type may be found in the Appendix of this dissertation, as well as computed standard deviations (σ), Table B-1 and Table B-2. Detailed descriptions of each IPCC factor are also provided.

Subsequently, an emission or sequestration factor ΔC_i was calculated for each transition and POINT_ID of interest, considering a period of 20 years of application of the new land management practice / land-conversion, described by

$$\Delta C_i = \frac{\left[\left(SOC_{REF_{c,s,i}} \times F_{LU_{c,s,i}} \times F_{MG_{c,s,i}} \times F_{I_{c,s,i}}\right)_{final} - \left(SOC_{REF_{c,s,i}} \times F_{LU_{c,s,i}} \times F_{MG_{c,s,i}} \times F_{I_{c,s,i}}\right)_{baseline}\right]}{D}, \quad (4)$$

where ΔC_i is the emission or sequestration factor and represents the yearly emitted or sequestered C per hectare in each POINT_ID, in $tC\ y^{-1} ha^{-1}$ and D is the period of application of the new land-use or land management practice, equal to 20 years.

Uncertainty of estimates

The computation described in the previous section provides average results for each situation. However, there is uncertainty associated with each factor which may affect the actual SOC Stocks and calculated Emission or Sequestration Factors. It therefore becomes relevant to consider the range of possible values for each transition and show how results may vary across soil type/climate-type combinations and set of land-use/management conditions.

Uncertainty estimates can be achieved with Monte Carlo (MC) Simulations, a mathematical technique which may be used for representing the range of outcomes of an uncertain event.

Using Python's 'Numpy' and 'Pandas' library, for each transition (T1, T2, T3A, T3B and T4), Monte Carlo simulations were performed, generating, for each $SOC_{REF_{c,s,i}}$ and for each SCF ($F_{LU_{c,s,i}}, F_{MG_{c,s,i}}, F_{I_{c,s,i}}$), a 1000 different random values based on the assumption of normal distributions and the uncertainty provided for each of the IPCC factors. SOC reference, SOC baselines, SOC alternatives and SOC Stock changes where then calculated for each of these new combinations of random values.

3.5 National sequestration potential

Having obtained annual changes of SOC stocks in mineral soils for all the listed transitions, we were then interested in obtaining an estimation of the maximum national sequestration potential, which considers, for each land-use or land management transition, the relevant area of cropland or grassland type per NUTS 3.

Data was retrieved from INE and the following datasets/indicators:

- Area of land occupied with grasslands and permanent pastures (ha) by location (NUTS I, II, II - 2013) and type (grasslands and permanent pastures) (2019), Table C-1;
- Area of land occupied by temporary crops (ha) by location (NUTS I, II, III - 2013), type (temporary crops) and area classes (2019), Table C-2;
- Percentage (%) of irrigated land by location (NUTS I, II, III – 2013) (2019), Table C-3;

The maximum National Sequestration Potential by sub-region (NUTS3) and transition was calculated as the potential to emit/sequester carbon per year associated to each of the simulated transition described in the section 3.5 over the totality of the land-available to each transition.

The following computation steps were taken:

1. Mean sequestration/emission factor per NUTS3, per transition, $\overline{\Delta C}$ (tC y^{-1} ha^{-1}), Table 3-8
2. Total Area per land-use (CL1, CL2, CL3, CL4, CL5, CL6, CL7, and GL1) per NUTS3 for each transition, $AT_{Transition,NUTS3=i}$ (ha)
3. Actual Area, $AA_{NUTS3=i}$ (ha) per transition
4. Total sequestration (tC y^{-1}) per region and per transition
5. Total national sequestration (tC y^{-1}) per transition

Table 3-8 - Mean sequestration/emission factor per transition per NUTS3, $\overline{\Delta C}$[9] (tC y^{-1} ha^{-1})

	$\overline{\Delta C}$ (tC y^{-1} ha^{-1})				
NUTS3	**T1**	**T2**	**T3A**	**T3B**	**T4**
Alentejo Central	0.04	0.04	-0.02	-0.06	0.45
Alentejo Litoral	0.06	0.05	-0.03	-0.10	0.54
Algarve	0.04	0.04	-0.01	-0.07	0.45
Alto Alentejo	0.04	0.04	-0.02	-0.06	0.46
Alto Minho	0.23	0.24	0.48	0.22	1.36
Alto Tâmega	0.16	0.17	0.29	0.17	1.21
Ave	0.24	0.24	0.48	0.23	1.23
Baixo Alentejo	0.04	0.04	-0.02	-0.06	0.43
Beira Baixa	0.05	0.06	0.03	-0.06	0.44
Beiras e Serra da Estrela	0.05	0.05	0.00	-0.03	0.65
Cávado	0.23	0.24	0.47	0.22	1.35
Douro	0.12	0.11	0.15	0.15	1.00
Lezíria do Tejo	0.04	0.04	-0.03	-0.07	0.65
Médio Tejo	0.06	0.07	0.05	-0.07	0.56
Oeste	0.04	0.04	-0.02	-0.07	0.45
Região de Aveiro	0.12	0.15	0.22	0.05	0.53
Região de Coimbra	0.08	0.09	0.09	-0.03	0.83
Região de Leiria	0.09	0.10	0.10	-0.06	0.84
Terras de Trás-os-Montes	0.06	0.06	0.03	-0.02	0.54
Tâmega e Sousa	0.23	0.24	0.48	0.23	1.27
Viseu Dão Lafões	0.18	0.16	0.27	0.19	0.98
Área Metropolitana de Lisboa	0.05	0.05	-0.03	-0.09	0.54
Área Metropolitana do Porto	0.24	0.24	0.48	0.23	0.99

The maximum possible area available per NUTS3 for each transition was obtained, based on land-use in 2019. It should be noted that results for different transitions cannot be added, since the same locations can be used for different Transitions (e.g., Transitions 1, 2, and 3, where the baseline stage is 'Rainfed Annual Crop').

[9] < 0 – Emission of C

Annual cropland crops' (CL1 and CL2) specific land-use categories as well as areas per region are available in Table C-1, in the Appendix section. Grassland (GL) areas are available in Table C-2 of the Appendix section.

For each transition (n), the total area to be considered for each NUTS3 sub-region (i) can be determined by

$$AT_{Transition_n,Baseline,NUTS3_i} = \sum_{LU_{Baseline}} A_{LU_{Baseline},NUTS3_i} \quad (5)$$

where $AT_{Transition_n,Baseline,NUTS3_i}$ is the total area available for the application of the transition per NUTS3 sub-region (ha) at baseline conditions and $A_{LU_{Baseline},NUTS3_i}$ is the land-use area of each specific land-use category eligible for each transition (Table 3-9), per sub-region.

Table 3-9 - Specific land-use categories at the baseline condition eligible for each transition

				Specific Land-Use Categories (INE, 2019)								
Transition			Land-use (Base-line)	Cereals	Pulses	Forage crops	Potatoes	Industrial crops	Horticultural Crops	Flowers and orna-mental plants	Other Temporary Crops	Poor grassland on clear ground
T1		Full to No-Till	CL1, CL2	x	x	x		x	x	x	x	
T2		Rainfed to Irrigated Annual Crops	CL1	x	x	x	x	x	x	x	x	
T3	T3A	Rainfed Annual Crops to Permanent Crops	CL1	x	x	x	x	x	x	x	x	
	T3B	Irrigated Annual Crops to Permanent Crops	CL2	x	x	x	x	x	x	x	x	
T4		Natural Poor Grasslands to Improved Grasslands	GL1									x

Crop area statistics from INE do not differentiate between rainfed and irrigated areas at crop level. However, information on share of irrigated areas is available from INE (Indicator 6698, ‘Percentage (%) of irrigated land by location’). For transitions where irrigation is relevant, the 2 indicators were combined, as described by

$$AA_{Transition_n,Baseline_{Irrigated}} = AT_{Transition_n,NUTS3_i} \times (\% \, Irrigated \, Area)_{NUTS3_i}, \tag{6}$$

$$AA_{Transition_n,Baseline_{Rainfed}} = AT_{Transition_n,NUTS3_i} \times (1 - \% \, Irrigated \, Area)_{NUTS3_i}, \tag{7}$$

where $AA_{Transition_n,Baseline_{Irrigated}}$ and $AA_{Transition_n,Baseline_{Rainfed}}$ represent the actual areas per NUTS3 in ha.

For transitions were the baseline conditions were ‘Irrigated’ - Transition 3B (Irrigated Annual Crops to Permanent Crops) and Transition 4 (Natural Poor Grasslands to Improved Grasslands), Equation (6) was used; on the other hand, and where the baseline conditions were rainfed - Transition 2 (Rainfed to Irrigated Annual Crops), Transition 3A (Rainfed Annual Crops to Permanent Crops) - Equation (7) was followed. In Transition 1 (Full to No-Till), baseline conditions are both irrigated and rainfed annual crops, hence, AA is equal to $AT.$ Irrigated Area (%) per NUTS3 is available in Table C-3 of the Appendix.

Finally, $\overline{\Delta C}$ per NUTS3 (tC y^{-1}) per transition was obtained by multiplying the respective $\overline{\Delta C}$ average per NUTS3 per transition (tC y^{-1} ha^{-1}) with the respective actual area (AA, ha). Finally, the total national C sequestration potential per transition can be obtained by adding all subregions’ $\overline{\Delta C}$.

3.6 IPCC Tier 1 adequacy

To understand the adequacy of IPCC’s Tier 1 methodology in estimating SOC Stocks, a comparison with LUCAS SOC values measured in the years 2009, 2015 and 2018 for cropland (CL1, CL2, CL3, CL4, CL5, CL6) and grassland (GL1) was done.

Data from IPCC and LUCAS is not immediately comparable for two reasons: SOC values from the LUCAS database are in gC kg^{-1}, while the IPCC estimated SOC values are in tC ha^{-1}; and IPCC estimates at 30 cm soil depth, while LUCAS measurements take place at 20 cm.

To allow comparison between these values, the LUCAS OC values need to be converted using

$$T_d = \sum_{i=1}^{k} (\rho_i \times P_i \times D_i) \times (1 - S_i) \times 10, \tag{8}$$

where T_d is the total amount of organic carbon over depth, d, (in tC ha^{-1}), ρ_i the bulk density in layer i (t m^{-3}), P_i the organic carbon in layer i (gC kg^{-1}), D_i the layer thickness (m), equal to 0.30 m, and S_i the fraction of the volume of coarse.

Which require as inputs (sampled) coarse values (coarse), soil organic carbon and bulk density values at a 30 cm depth (BD_030).

In 2018, the LUCAS Soil survey sampled a total of 476 topsoil in Mainland Portugal, of which a total of 181 were within the land-use categories of managed cropland (CL1, CL2, CL3, CL4, CL5, CL6) and grassland (GL1). Coarse (coarse_18), bulk density at 0-10, 0-20 and 20-30 cm depth (BD_010, BD_020, BD_2030) and organic carbon, at 0-20 cm depth and 20-30 cm depth (OC_18 (0-20cm), OC_2030cm) values were available for a total of 65 points (2018_1)[10]. For the remaining 116 other points (2018_2), only coarse and organic carbon (OC_18) at a 20 cm depth was available.

In 2015, a total 190 grassland and cropland sites in Mainland Portugal were sampled and 207 in 2009. In both years, this sampling resulted in datasets which include coarse (coarse) values and organic carbon values at a 20 cm depth (OC), but no available bulk density values.

The missing bulk density and 20-30cm depth values were estimated using the results of 2018's sampled values (2018_1) for which this information is available (n = 65), using the following methodology:

1. Obtaining the average SOC concentration in the 0-30 cm (n = 65);
2. Obtaining an average ratio between SOC concentration in the layer 20-30cm and the layer 0-20cm, $\bar{\boldsymbol{r}}_{\boldsymbol{OC_{2018\_1}}}$ (n = 65)
    a. using this ratio to obtain an estimate of SOC concentration in the layer 0-30cm in all points where this information is missing (n = 116 for 2018, n = 190 for 2015, n = 207 for 2009);
3. Obtaining the relationship between SOC concentration in the layer 0-30cm and Bulk Density in the same layer (n = 65)
    a. Using this relationship to estimate bulk density in the layer 0-30cm in all points where this information is missing (n = 116 for 2018, n = 190 for 2015, n = 207 for 2009).

[10] For clarification purposes, when referring to samples of:

- Points of 2018 with coarse, BD_010, BD_020, BD_2030, OC_18 (0-20cm), OC_2030 values, we refer to those as 2018_1
- Points of 2018 where only coarse (coarse_18) and organic carbon (OC_18) at a 20 cm depth were available, we refer to 2018_2.

Obtaining organic carbon and bulk density at 0-30 cm depth

Where values of SOC at 0-20 cm and SOC at 20-30cm depth were provided, for the year of 2018 (n = 65), SOC at 0-30 cm depth, for each point (i) can be obtained through a simple weighted average between the two

$$OC_{0-30_{i\,y=2018\_1}} = \frac{OC_{20-30_i} + 2 * OC_{0-20_i}}{3}, \quad (9)$$

with $OC_{0-30_{i\,y=2018\_1}}$ in gC kg^{-1} and where i represents each of the 65 georeferenced point in 2018_1.

Bulk Density (BD) at 0-30cm for each point (n = 65) was obtained by averaging the measured values at all depths and is described by

$$BD_{0-30_i} = \frac{BD_{0-10_i} + BD_{10-20_i} + BD_{20-30_i}}{3}, \quad (10)$$

with BD_{0-30_i} in t m^{-3}.

Obtaining an average ratio between OC_2030 and OC_020

This ratio provides the relationship between SOC at 20-30 cm and SOC at 0-20 cm depths for each point (i) where LUCAS values existed (n=65) and will be further used to determine $OC_{20-30_i,y=2018\_2,2015,2009}$, as described by

$$\bar{r}_{OC_{2018\_1}} = \frac{\sum_{i=1}^{65} \frac{OC_{20-30_i}}{OC_{0-20_i}}}{65}, \quad (11)$$

where $\bar{r}_{OC_{2018\_1}}$ is unitless and i represents each of the 65 georeferenced point in 2018_1.

Obtaining the relationship between SOC and bulk density at 0-30cm

The relationship between organic carbon and bulk density has been extensively documented in the literature, and it is commonly employed to estimate carbon sinks (Post et al., 1982). Typically, this association exhibits an inverse pattern, meaning that as soil organic carbon (SOC) levels increase, bulk density (BD) tends to decrease, and vice versa. The nature of this relationship can be represented using various mathematical models, such as logarithmic, polynomial, or linear models (SAKİN, 2012). By comparing the measured values of SOC at 30 cm depth (OC_030) and BD at 30 cm depth (BD_030) for 2018_1 (n = 65), we can draw a relationship between SOC and BD as shown in Figure 3-8.

Then, for the remaining samples where BD_030 was not measured (2015, 2009 and 2018_2), we followed the following computation steps:

1 - Obtaining OC_2030 (Y=2018_2, 2015, 2009), eq. (12)

2 - Obtaining OC_030 (Y=2018_2, 2015, 2009), eq. (13)

3 - Obtaining BD_030 (Y=2018_2, 2015, 2009), eq. (14)

$$OC_{20-30_{i,y=2018_2,2015,2009}} = \bar{r}_{OC_{2018}} * OC_{0-20_i}, \quad (12)$$

$$OC_{0-30_{i,y=2018\_2,2015,2009}} = \frac{OC_{20-30_i} + 2 * OC_{0-20_i}}{3}, \quad (13)$$

where $OC_{0-30_{i,y=2018\_2,2015,2009}}$ is the OC at 0-30 cm depth in point i, for the relevant years and OC_{20-30_i} is OC at 20-30 cm depth in point i, OC_{0-20_i} is OC at 0-20 cm depth in point I, in gC kg^{-1} and assuming a uniform distribution of SOC in the topsoil profile.

BD at 30 cm depth for all years and points where BD (0-30 cm) was not measured can be obtained by extrapolation from the value of OC

$$BD_{0-30_{i,y=2018\_2,2015,2009}} = -0.188 * ln\,(OC_{0-30}) + 1.6925, \quad (14)$$

with $BD_{0-30_{i,y=2018\_2,2015,2009}}$ in t m^{-3}.

Finally, we were able to obtain LUCAS SOC stocks for all 578 points in the years 2009, 2015 and 2018, in tC ha^{-1}, using eq. (8).

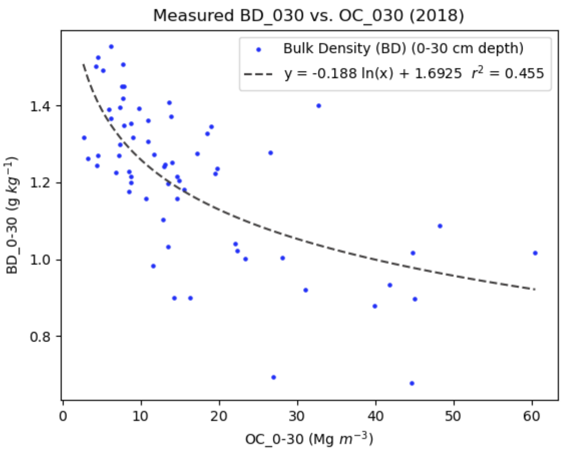


Figure 3-8 - Bulk density (0-30 cm depth) vs. measured organic carbon (0-30 cm depth), LUCAS 2018_1, n = 65; y = -0.188 ln(x) + 1.6925 (best fitting curve), r^2 = 0.455 (coefficient of determination)

Developing alternatives to the baseline scenario

Since we are interested in comparing the LUCAS SOC values with the SOC stocks following IPCC's Tier 1 methodology, and since the latter depend on a set of prescribed conditions (defined by us and which may or may not reflect the current land management situation in the different sites of Portugal), which then dictate the value of each stock change factor, we develop a 3-case-scenario (Table 3-10) to add nuance to our assessment:

i. A worst-case scenario – whereby all land-use, management and input factors are set to their **lowest** values;
ii. A baseline scenario, with a set of conditions equal to that previously defined in section "Computing $SOC_{Baseline}$ stocks for grassland and cropland" of IPCC Tier 1 methodology;
iii. A best-case scenario, whereby all land-use, management and input factors are set to their **highest** values.

With this, we develop a range of possible IPCC values for each land-use, against which LUCAS SOC values can be compared. It should be noted that actual management practices being applied by farmers in each specific location and time are unknown. The conversion of these characteristics to average values can be found in Table B-1 and Table B-2.

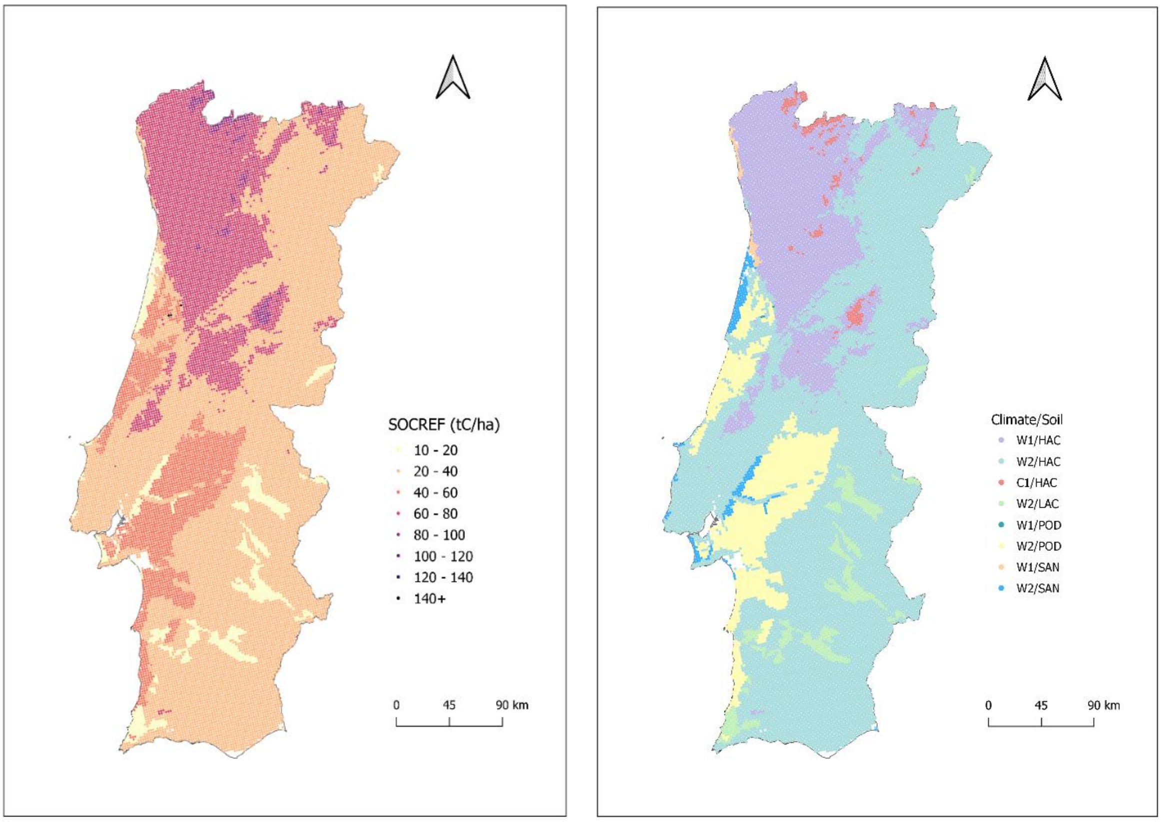
Table 3-10 – IPCC land-use and land management conditions to characterize SCFs for each land-use type and scenario (best, baseline and worst)

Land Use Type	**Scenarios**	**IPCC land-use and land management conditions** F_{LU} **Land Use**	F_{Mg} **Management**	F_I **Input**
Rainfed Annual Crops (CL1)	Worst	Long-term cultivated	Full	Low
	Baseline		Full	Medium
	Best		No-till	High (w/ manure)
Irrigated Annual Crops (CL2)	Worst	Long-term cultivated	Full	Low
	Baseline		Full	Medium
	Best		No-till	High (w/ manure)
Rice Paddies (CL3)	Worst	Paddy Rice	NA[8]	NA[8]
	Baseline		NA[8]	NA[8]
	Best		NA[8]	NA[8]
Vineyards (CL4)	Worst	Tree Crop	Full	Low
	Baseline		Reduced	Low
	Best		No-till	High (w/ manure)
Olive Groves (CL5)	Worst	Tree Crop	Full	Low
	Baseline		Reduced	Medium
	Best		No-till	High (w/ manure)
Other Permanent Crops (CL6)	Worst	Tree Crop	Full	Low
	Baseline		Reduced	Medium
	Best		No-till	High (w/ manure)
Pastures (GL1)	Worst	All	Severely Degraded	Medium
	Baseline		High Intensity grazing	Medium
	Best		Improved	High

4 Results and Discussion

4.1 IPCC Tier 1 methodology

SOC Reference stocks



a) *b)*

Figure 4-1 - IPCC SOC_{REF} stocks (tC ha^{-1}) a) and IPCC climate/soil combination b)

Eight distinct SOC_{REF} values were obtained, each corresponding to one of the eight unique climate and soil combinations. SOC_{REF} values for each corresponding unique climate and soil combination are shown in Table 4-1, as well as respective shares and area.

Areas with high activity clay soils (HAC) and a warm temperate dry climate (W2) are the most frequent (61%) and leads to a SOC_{REF} value of 24 tC/ha. The highest estimated SOC_{REF} (143 tC/ha) occurs in areas with a combination of Podzol soils (POD) and warm temperate moist climate (W1).

The North of Portugal would accumulate the highest carbon stock values, while Baixo, Central and Alto Alentejo have the lowest reference carbon stocks. A simple arithmetic average of the SOC_{REF} values obtained for the 2,2139 points, we obtain a national of SOC_{REF} of 36 tC/ha, approximately **320 MtC**, when we consider the total area of Mainland Portugal.

Table 4-1- SOC_{REF} stocks (tC ha^{-1}) for each climate/soil combination and share (%)

Climate Classification	Soil Classification	SOC_{REF} (tC/ha)	Share (%)	Area (ha)
Cold Temperate Moist (C1)				
	High Activity Clay (HAC)	81	1.2%	102,930
Warm Temperate Moist (W1)				
	High Activity Clay (HAC)	64	21.5%	19,155
	Podzols (POD)	143	0.01%	1,206
	Sandy (SAN)	36	0.30%	26,938
Warm Temperate Dry (W2)				
	High Activity Clay (HAC)	24	61.1%	5,440,453
	Low Activity Clay (LAC)	19	3.8%	337,339
	Podzols (POD)	51.5	11%	978,244
	Sandy (SAN)	10	1.1%	98,910
	Average SOC_{REF}	**36**	**Total (ha)**	8,901,500

.

$SOC_{Baseline}$ stocks

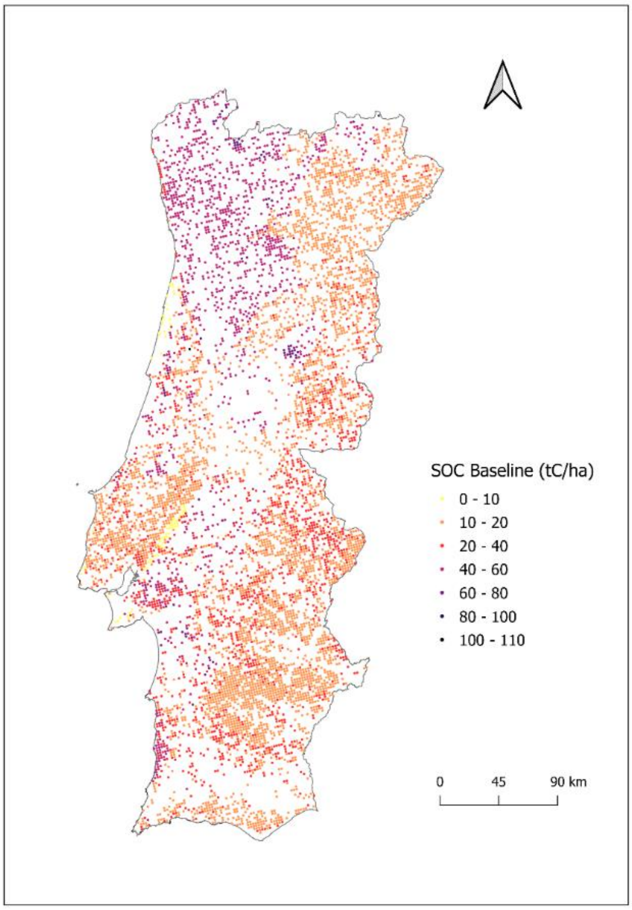


Figure 4-2 - $SOC_{Baseline}$ stocks (tC ha^{-1}) for cropland and grassland

When land-use and agricultural practices are considered, the carbon stocks are lower, when compared to the SOC_{REF}, which, as previously mentioned, is an aspirational value for undisturbed soils.

We observed that the climate-soil combinations and land-use, land management conditions which offer the highest $SOC_{BASELINE}$ stocks per hectare are as follows:

- Irrigated Annual Crops of Warm Temperate Moist (W1), Podzol (POD) ($SOC_{BASELINE}$ = 109.5 tC/ha);
- Vineyards, Warm Temperate Moist (W1) and Podzol (POD) ($SOC_{BASELINE}$ = 100 tC/ha);
- Pastures, Cold Temperate Moist (C1), High Activity Clay (HAC) ($SOC_{BASELINE}$ = 72.9 tC/ha).

In contrast, the lowest $SOC_{BASELINE}$ values per hectare were obtained for:

- Vineyards, Warm Temperate Dry (W2) and sandy soils (SAN) ($SOC_{BASELINE}$ = 6.8 tC/ha);
- Olive groves, Warm Temperate Dry (W2) and sandy soils (SAN) ($SOC_{BASELINE}$ = 7.1 tC/ha);
- Rainfed annual crops, Warm Temperate Dry (W2) and sandy soils (SAN) ($SOC_{BASELINE}$ = 7.6 tC/ha);

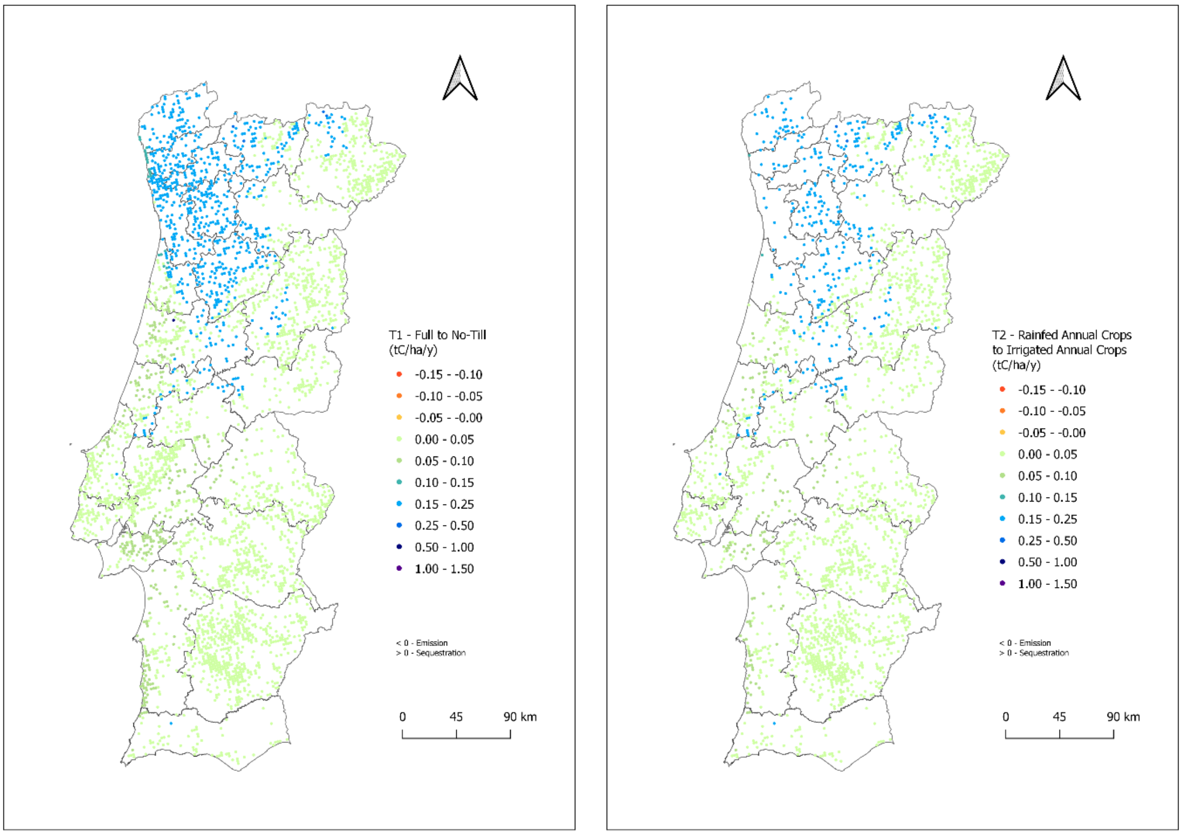
These results are in agreement with what we have seen in our review of the literature, whereby higher SOC stocks are usually found in cooler or wetter/humid regions (Scharlemann et al., 2014) such as Cool Temperate Moist (C1) regions, and in soils with higher clay content such as HAC.

Table 4-2 - SOCBaseline stocks (tC ha^{-1}) per land-use (2018) and climate/soil combination and cropland and grassland share (%)

Land-use (2018)		$SOC_{Baseline}$ (tC/ha)	Cropland and Grassland Share (%)
Irrigated Annual Crops			14.7%
Cold Temperate Moist (C1)			0.01%
	High Activity Clay (HAC)	62.9	0.01%
Warm Temperate Moist (W1)			5.8%
	High Activity Clay (HAC)	49.0	5.5%
	Podzols (POD)	109.5	0.01%
	Sandy (SAN)	27.6	0.3%
Warm Temperate Dry (W2)			8.9%
	High Activity Clay (HAC)	19.0	6.0%
	Low Activity Clay (LAC)	15.0	0.2%
	Podzols (POD)	40.7	2.2%
	Sandy (SAN)	7.9	0.5%
Olive Groves/Other Permanent Crops			21.0%
Warm Temperate Moist (W1)			0.9%
	High Activity Clay (HAC)	48.4	0.9%
Warm Temperate Dry (W2)			20.2%
	High Activity Clay (HAC)	17.1	18.4%
	Low Activity Clay (LAC)	13.5	1.0%
	Podzols (POD)	36.7	0.7%
	Sandy (SAN)	7.1	0.2%
Pastures			21.7%
Cold Temperate Moist (C1)			0.7%
	High Activity Clay (HAC)	72.9	0.7%
Warm Temperate Moist (W1)			1.3%
	High Activity Clay (HAC)	57.6	1.3%
	Sandy (SAN)	32.4	0.0%
Warm Temperate Dry (W2)			19.7%
	High Activity Clay (HAC)	21.6	16.7%
	Low Activity Clay (LAC)	17.1	1.4%
	Podzols (POD)	46.4	1.4%
	Sandy (SAN)	9.0	0.2%
Rainfed Annual Crops			34.2%
Cold Temperate Moist (C1)			0.1%
	High Activity Clay (HAC)	56.7	0.1%
Warm Temperate Moist (W1)			4.9%
	High Activity Clay (HAC)	44.2	4.9%
	Sandy (SAN)	24.8	0.0%
Warm Temperate Dry (W2)			29.2%
	High Activity Clay (HAC)	18.2	24.9%
	Low Activity Clay (LAC)	14.4	2.1%
	Podzols (POD)	39.1	2.0%
	Sandy (SAN)	7.6	0.2%
Rice Paddies			1.3%
Warm Temperate Dry (W2)			1.3%
	High Activity Clay (HAC)	32.4	0.7%
	Podzols (POD)	69.5	0.4%
	Sandy (SAN)	13.5	0.2%
Vineyards			7.2%
Warm Temperate Moist (W1)			1.4%
	High Activity Clay (HAC)	44.5	1.3%
	Podzols (POD)	99.5	0.01%
Warm Temperate Dry (W2)			5.8%
	High Activity Clay (HAC)	16.3	5.0%
	Low Activity Clay (LAC)	12.9	0.2%
	Podzols (POD)	34.9	0.4%
	Sandy (SAN)	6.8	0.1%
	Total		**100%**

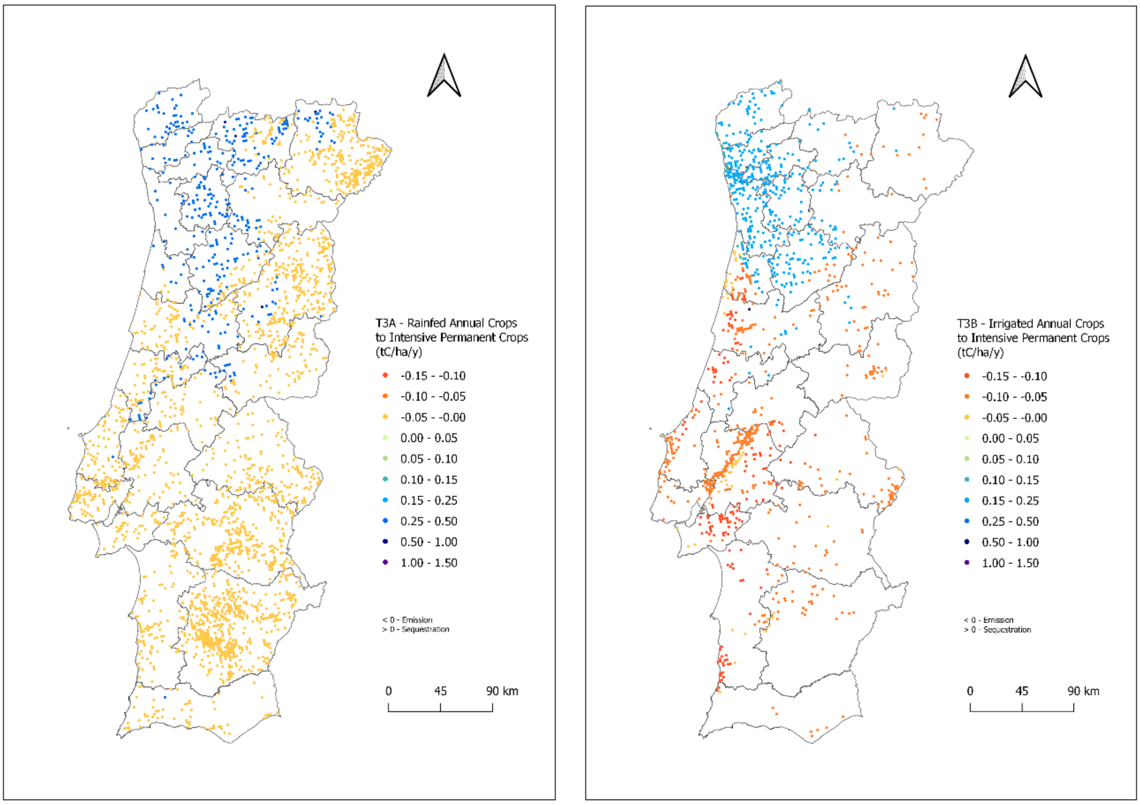
Annual changes of soil organic carbon (SOC) stocks for transitions in cropland and grassland (ΔCi)

In this section we present soil C emission/sequestration factors in different sites in Mainland Portugal for each of the proposed changes in land-use and land management practices (Figure 4-5). Table 4-3 summarizes the highest and lowest soil C emission/sequestration factors obtained per transition and the correspondent soil/climate combination.



a) *b)*

Figure 4-3 – IPCC sequestration factors (tc ha^{-1} y^{-1}), transition 1 – annual crops, full to no-till, n = 3,508 a), transition 2 – rainfed annual crops to irrigated crops, n = 2,455, b)



a) *b)*

Figure 4-4 - IPCC emission/sequestration factors (tC ha^{-1} y^{-1}), transition 3a – rainfed annual crops to intensive permanent crops, n = 2,455, a), transition 3b – irrigated annual crops to permanent crops, n = 1,053, b)

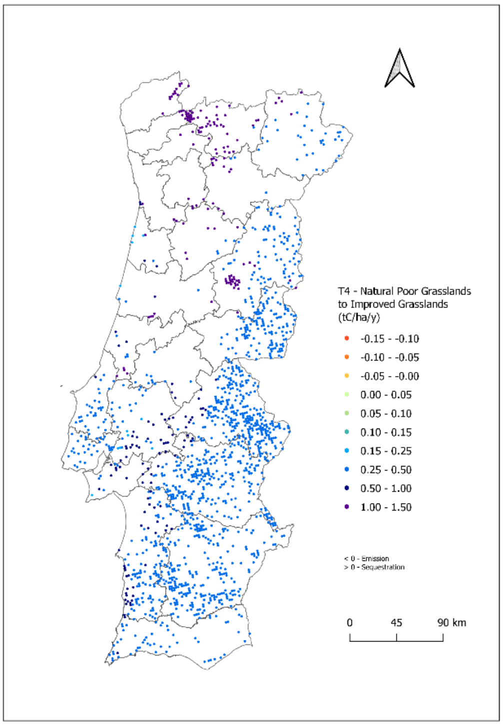


Figure 4-5 – IPCC sequestration factors (tC ha^{-1} y^{-1}) for transition 4 – natural poor grasslands to improved grasslands, n = 1,557

The transition of annual crops from full to no-till (T1) shows C sequestration over all of Mainland Portugal, with a maximum yearly sequestration of 0.55 tC ha^{-1} y^{-1} and a global average of 0.08 tC ha^{-1} y^{-1}. In Europe, zero-tillage has been estimated to potentially sequester 0.4 tC ha^{-1} y^{-1} (Freibauer et al., 2004). For dryland in Mediterranean conditions, a modelled approach predicted that no-tillage could sequester 0.25 tC ha^{-1} y^{-1}, in the first 20 years (0-30 cm soil layer) (Álvaro-Fuentes et al., 2009), while the average obtained in this work, for a W2 (warm temperate dry) climate resulted in 0.05 tC ha^{-1} y^{-1}. Hence, the potentials obtained using the IPCC Tier 1 Methodology, for the application of no-tillage, are lower than estimates found in literature.

The application of irrigation to rainfed annual crops (T2) also improves SOC sequestration, as expected, with a maximum yearly sequestration of 0.3 tC ha^{-1} y^{-1} and a global average of 0.07 tC ha^{-1} y^{-1}. Sequestration factors are higher in areas with higher SOC_{REF}, i.e., cooler and wetter climate regions.

While land-use conversion of annual to permanent cropland has been estimated to potentially sequester 0.6 tC ha^{-1} y^{-1}, for Europe (Freibauer et al., 2004), and 0.3 tC ha^{-1} y^{-1} globally (Ledo et al., 2020), Transitions 3-A and 3-B from this work show sites where emission of C is likely to occur, contrasted by sites where sequestration is likely to occur, with a global national average of 0.05 tC ha^{-1} y^{-1}. Here, conversion to permanent crop appears to be particularly unfavourable for warm and dry regions (W2). These results highlight how the application of the same land-use and land management practices in different sites (with distinct soil properties and climate) may induce different SOC changes.

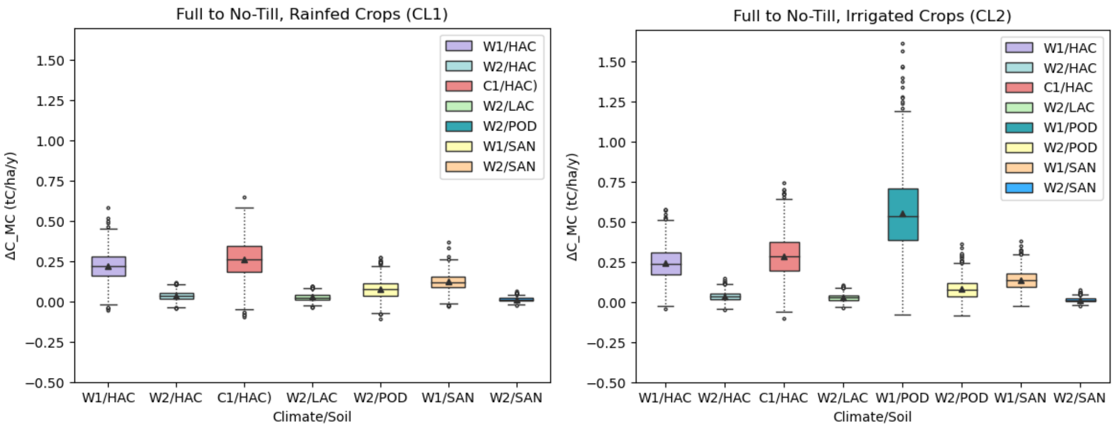
Table 4-3 - Highest and Lowest ΔC_i (tC ha^{-1} y^{-1}) per transition and corresponding region and soil/climate combination. ΔC_i Values < 0 represent emission of C, n - number of POINT_ID in each transition

		Transition	Highest ΔC_i		Lowest ΔC_i	
			Climate/Soil	tC ha^{-1} y^{-1}	Climate/Soil	tC ha^{-1} y^{-1}
T1		**Full to No-Till** (n = 3,508)	W1/POD	**0.55**	W2/SAN	**0.02**
T2		**Rainfed to Irrigated Crops** (n = 2,455)	C1/HAC	**0.31**	W2/SAN	**0.02**
T3	T3A	**Rainfed Annual Crops to Perennial Crops** (n = 2,455)	C1/HAC	**0.55**	W2/POD	**-0.05**
T3	T3B	**Irrigated Annual Crops** (n=1,053)	W1/POD	**0.53**	W2/POD	**-0.13**
T4		**Natural to Improved Grasslands** (n = 1,557)	C1/ HAC	**1.5**	W2/SAN	**0.18**

Overall, the transition from Natural Poor Grasslands to Improved Grasslands (T4) is likely to provide the highest SOC sequestration potential (1.5 tC y^{-1} ha^{-1}) obtained for sites with a soil/climate combination of High Activity Clay (HAC) soil and Cold Temperate Dry (C1) climate.

IPCC variability

Considering Transition 1, where rainfed annual crops and irrigated annual crops are subject to a management change of full to no-till, we observe that for different climate-soil combinations, the sequestration potentials vary. The W1/POD combination shows the highest mean sequestration value in irrigated crops and greater variability, with values spreading from -0.25 to 1.50 tC^{-1} ha^{-1} y^{-1}, but low representativeness in terms of area, as we may observe in Figure 4-1 b).



a) *b)*

Figure 4-6 - MC distribution of sequestration/emission factors for transition 1 – annual crops, full to no-till, per climate/soil combination, rainfed crops (CL1) a), irrigated crops (CL2) b) [11]

All climate-soil combinations show greater than zero ΔC, indicating, as previously mentioned section "Annual changes of soil organic carbon (SOC) stocks for transitions in cropland and grassland (ΔCi)", that sequestration scenarios are the most likely to occur if this transition is applied. Nevertheless, and for any of the soil/climate combinations, emission (< 0) scenarios may also occur. The W2/POD and C1/HAC combination show the biggest variability.

[11] Descriptions of each element of the boxplots and what these represent are available in section D of the Appendix.

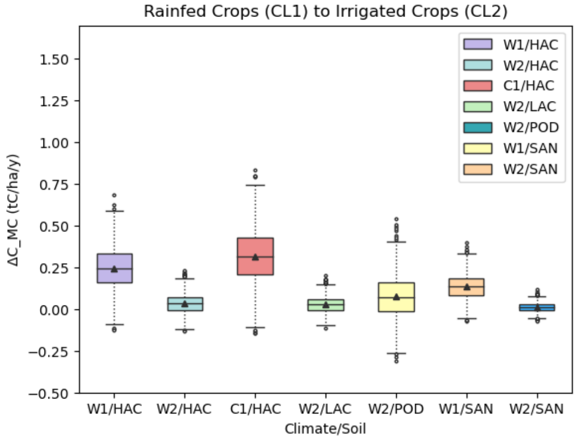
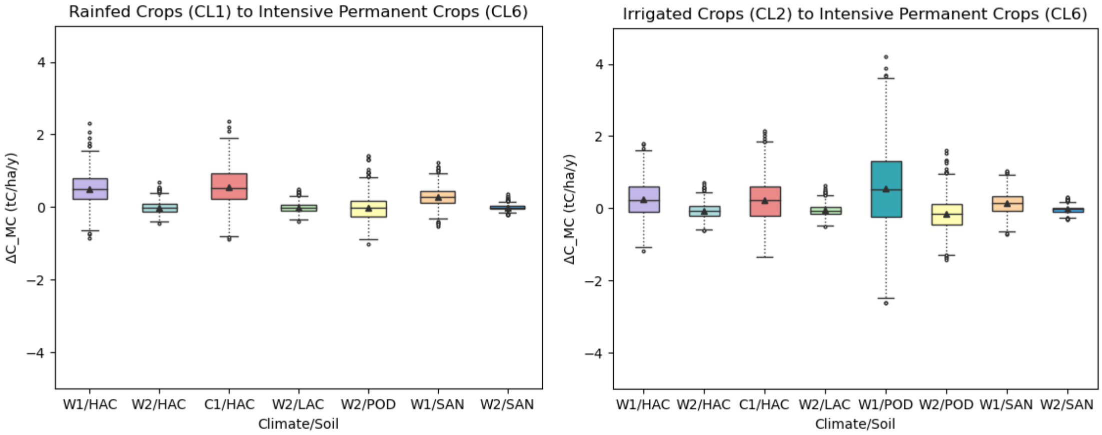


Figure 4-7 - MC distribution of sequestration/emission factors for transition 2 - rainfed annual crops to irrigated crops (CL1 to CL2) per climate/soil combination [11]

All climate-soil combinations show ΔC means greater than zero, indicating, as previously mentioned that sequestration scenarios are the most likely to occur if this transition is applied. Nevertheless, and for any of the soil/climate combinations, emission (< 0) scenarios may occur. The W2/POD and C1/HAC combination show the biggest variability.



a) *b)*

Figure 4-8 – MC distribution of sequestration/emission factors for transition 3a - rainfed annual crops to intensive permanent crops, a) and transition 3b - irrigated annual crops to intensive permanent crops, b), per climate/soil combination [11]

Transitions 3A and 3B show the lowest mean sequestration potentials for all soil/climate combinations, in comparison to the other transitions. Particularly, the W2/POD combination shows the lowest expected ΔC, -0.05 and -0.13 (tC ha^{-1} y^{-1}) for T3A and T3B respectively. The W1/POD combination shows the highest ΔC mean (>0) but also the highest variability. Here, and although the expected scenarios are of either low sequestration or low emission of C, opposing results may also be obtained, from high emission to high sequestration.

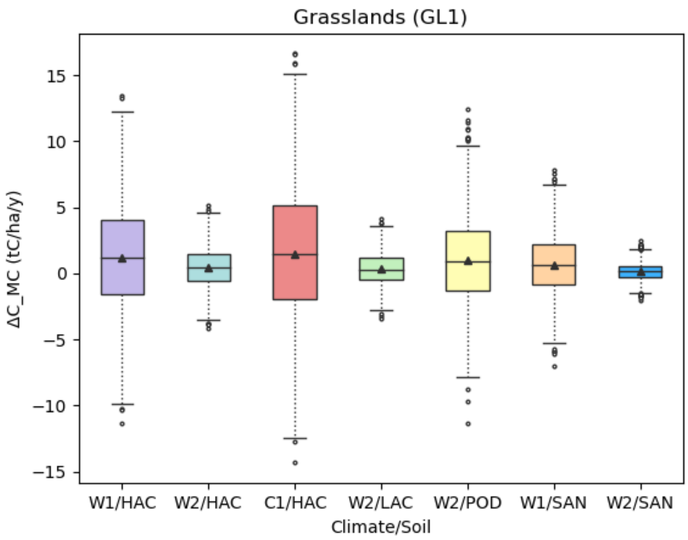


Figure 4-9 – MC distribution of sequestration/emission factors for t4 - poor natural grasslands to improved grasslands, per climate/soil combination [11]

T4 shows the highest overall mean sequestration potentials for all soil/climate combinations, in comparison with the other land-use and land management changes tested in this Thesis. Figure 4-9 shows that nevertheless, emission scenarios may also result, and although unlikely, these can be potentially very high for W1/HAC and C1/HAC combinations.

This estimation allows us to visualize how the previously obtained results for emission/sequestration potentials are not definitive, since for each factor there is an associated variability. Consequently, it's possible that for certain transitions and soil/climate combinations, where sequestration estimates were higher, a much lower sequestration outcome than initially anticipated may result.

4.2 National sequestration potential

The transition from natural poor grasslands to improved grasslands is the one which offers the highest overall sequestration potential (0.39 MtC y^{-1}). The lowest overall sequestration potential is attributed to Transition 3B, Irrigated Annual crops to Intensive Perennial crops (0.007 MtC y^{-1}) (Table 4-5). These potentials not only highlight how region-specific climatic and edaphic factors may affect C sequestration, but also account for the potential area availability for application of such practices, information which may be helpful to inform decision makers, especially at a local level.

Detailed emission/sequestration values in tC y^{-1} per transition per NUTS3 subregion and total national sequestration potentials per transition, in tC y^{-1}, MtC y^{-1} and MtCO$_2$ y^{-1} can be found in the Appendix section, Table D-1.

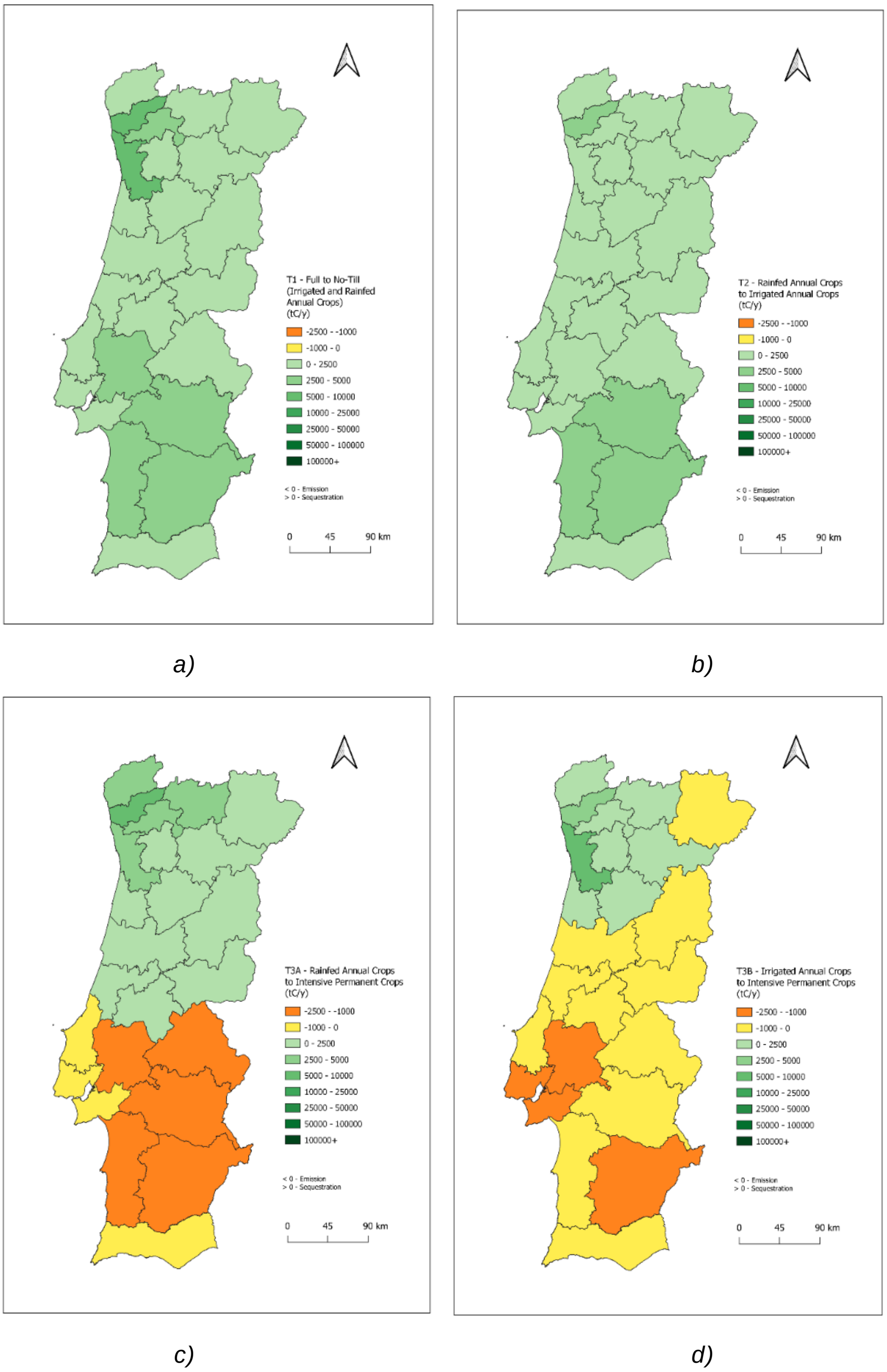


Figure 4-10 - National sequestration potential (tC y^{-1}), transition 1 – annual crops, full to no-till, a), transition 2 – rainfed annual crops to irrigated crops, b), transition 3a - rainfed annual crops to intensive permanent crops, c) and transition 3b - irrigated annual crops to intensive permanent crops, d)

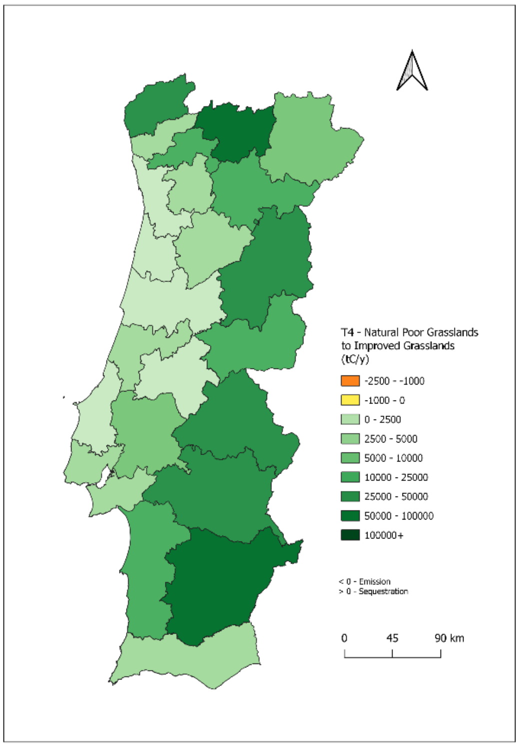


Figure 4-11 - National sequestration potential (tC y^{-1}), t4 - poor natural grasslands to improved grasslands

For both Transition 3A and 3B (Figure 4-10), sequestration as well as emission is possible, depending on the region considered, as highlighted in Table 4-4.

Table 4-4 – Sub-regions with highest and lowest sequestration potentials per transition (tC y^{-1})

		Transition	**Highest**		**Lowest**	
			Sub-region (NUTS3)	tC y^{-1}	Sub-region (NUTS3)	tC y^{-1}
T1		Full to No-Till	Cávado	6,297	Algarve	432
T2		Rainfed to Irrigated Crops	Baixo Alentejo	3,685	Algarve	331
T3	**T3A**	Rainfed Annual Crops to Perennial Crops	Cávado	5,142	Baixo Alentejo	-2,265
	T3B	Irrigated Annual Crops to Perennial Crops	Área Metropolitana do Porto	5,293	Lezíria do Tejo	-1,635
T4		Natural Poor Grasslands to Improved Grasslands	Baixo Alentejo	54,595	Região de Aveiro	109

As previously mentioned in sections 2.3 and 2.4 of this dissertation, land-use and land management transitions which promote soil C sequestration may induce other environmental side effects such as increasing emissions of other GHGs but also, improved biodiversity and enhanced ecosystem services. In our assessment of the national sequestration potential, such environmental effects were not accounted for, but we find it relevant to point out possible effects which may follow with each transition. It is also important to highlight that a feasibility assessment was not carried out. Feasibility refers to, for example, the water and nutrient availability for fertilization to apply land management changes. In our assessment, only theoretical areas were considered, and water availability was not assessed. Hence, we believe it to be important to mention some constraints to the application of the land-use and land management changes considered in this assessment.

Table 4-5 summarizes the national sequestration potentials per transition, % contribution to EU GHG mitigation from soils, other environmental effects and possible feasibility constrains.

Table 4-5 - National sequestration potential per transition, possible environmental effects and feasibility constraints

Transition			National Sequestration Potential		Other Environmental Effects	Feasibility Constraints
			MtC y^{-1}	Mt CO_2 y^{-1}		
T1		Full to No-Till	0.06	**0.21**	Enhancing N_2O emissions due to anaerobic conditions in the soils and from an increased use of fertilizers (Freibauer et al., 2004)	Fertilizer availability Farmer's adherence to new practices
T2		Rainfed to Irrigated Crops	0.04	**0.13**	Water pumping for irrigation may lead to extra CO_2 emissions (Schlesinger, 1999)	Water availability for irrigation Farmer's adherence to new practices
T3	T3A	Rainfed Annual Crops to Perennial Crops	0.02	**0.08**	Enhanced soil biodiversity	Water availability for irrigation
T3	T3B	Irrigated Annual Crops to Perennial Crops	0.01	**0.03**	Enhanced C in above and below ground biomass	Farmer's adherence to new practices
T4		Natural Poor Grasslands to Im-proved Grasslands	0.39	**1.43**	Increased N_2O emissions from enhanced fertilization (Schlesinger, 1999)	Fertilizer availability. Farmer's adherence to new practices

4.3 IPCC Tier 1 adequacy

Comparison with LUCAS

Our results show that IPCC's Tier 1 methodology tends to underestimate SOC stocks when compared to LUCAS in-situ sampled OC in 2009[12], 2015, and/or 2018 (total 578 points). The scatter plot shown in Figure 4-12 helps visualize these results. The diagonal red line represents an ideal scenario whereby all IPCC SOC stocks would match the observed results provided by LUCAS. Any data points which are below that line represent a potential underestimation of the IPCC Tier 1 methodology, whereas any points above that line represent a potential overestimation of the methodology.

While differences around the diagonal were naturally expected, we can observe that, in the large majority of the points, the IPCC estimated values show lower OC values than the corresponding LUCAS points (80%; n = 464/578). Conversely, there are sites where the IPCC estimates are higher than LUCAS, but they represent a much lower proportion of the points (20%; n = 114/578). This pattern, combined with the absolute magnitude of the differences leads to the general conclusion that the IPCC tends to underestimate the C content of soils, compared to values observed in LUCAS.

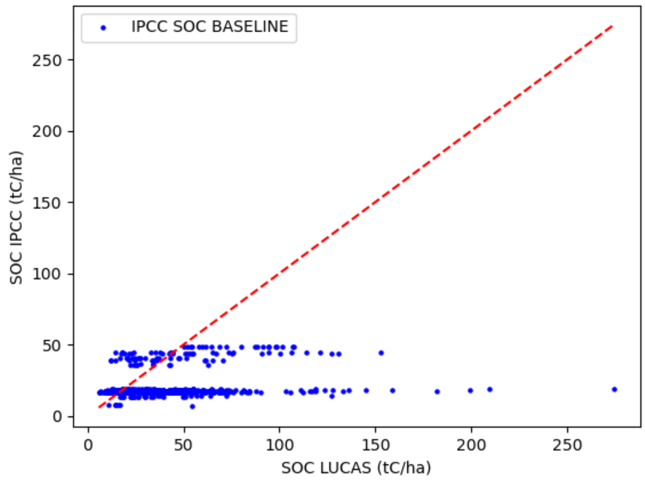


Figure 4-12 - SOC IPCC vs. SOC LUCAS (2009, 2015, 2018), n = 578

Possible reasons for the observed differences

We were interested in analysing how different factors could help explain the observed differences by considering the following hypotheses:

i. The IPCC Tier 1 methodology is systematically underestimating SOC stocks;
ii. The IPCC Tier 1 underestimated SOC Stocks affect only some soil types, some climate types and/or some land-uses;
iii. The method used to make LUCAS and IPCC compatible is overestimating LUCAS results.

[12] When comparing 2009 LUCAS values with IPCC estimates we use, for the latter, the land-use information available for the year of 2010, provided by COS/DGT.

Let us explore these options and test their veracity.

I. The IPCC Tier 1 methodology systematically underestimates SOC stocks

The application of the IPCC Tier 1 methodology allows for different values for the same point, depending on the parameters used to describe Land-Use, Management and Input Stock Change Factors. The y axis values in Figure 4-12 were set using the conditions described as "Baseline Scenario". To test whether this was the reason for underestimation (i.e. stock change factors are not appropriately reflecting the reality), we compared the LUCAS values with an IPCC Best Case Scenario (described in section "Developing alternatives to the baseline scenario").

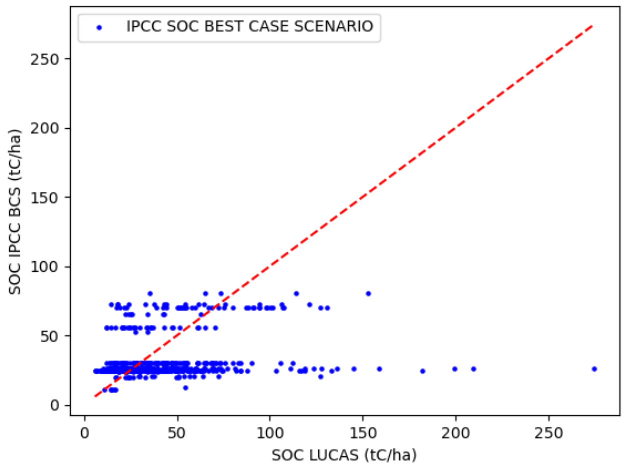


Figure 4-13 – SOC IPCC BCS vs. SOC LUCAS (2009, 2015, 2018), n = 578.

As expected, and as we may observe in Figure 4-13, this reduces the number of underestimated points, but the general pattern of underestimation still prevails (60%, 344/578 points). Although the choice of our baseline scenario conditions may be somewhat 'restrictive', its impact is not sufficient to justify all underestimation and it is nevertheless unlikely that all farmers are using all the best possible management practices foreseen by the IPCC methodology.

The Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 2, "Generic Methodologies Applicable to Multiple Land-Use Categories" provides a decision-tree for identification of the appropriate tier to estimate changes in carbon stocks in mineral soils by land-use category (Figure 4-14).

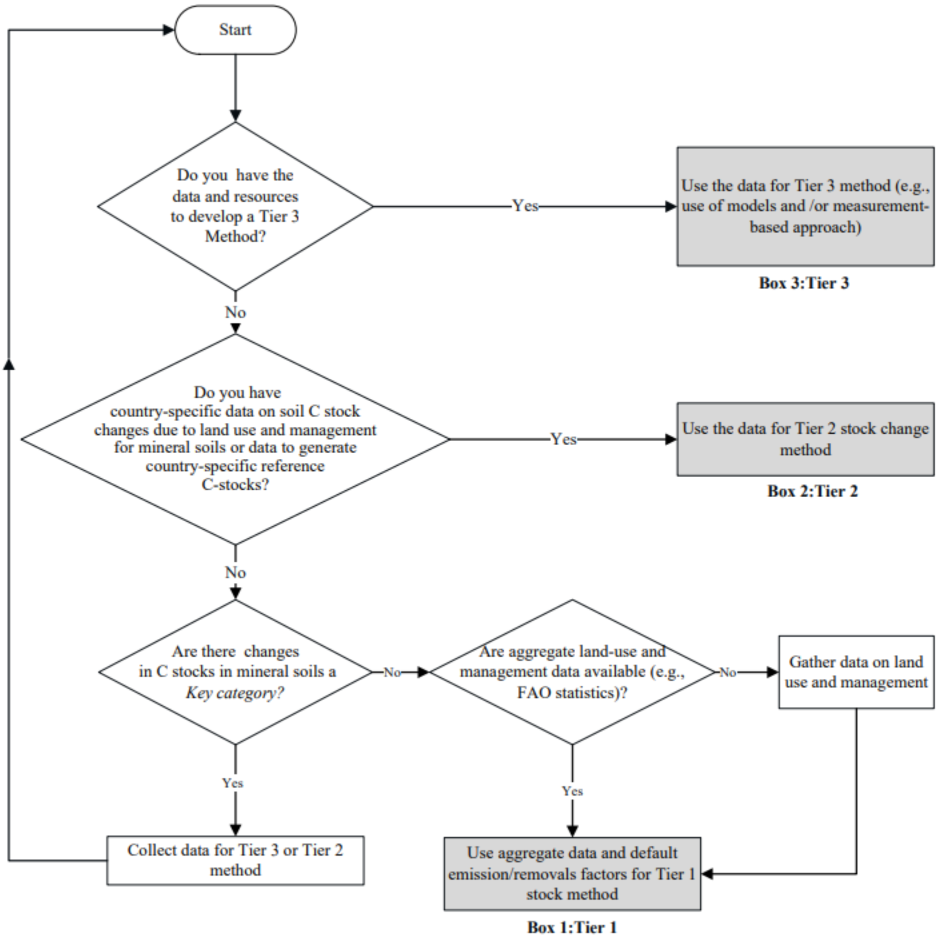
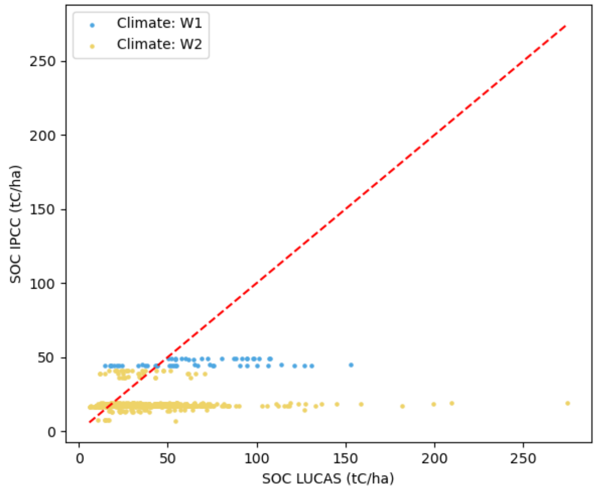


Figure 4-14 – Generic decision tree for identification of appropriate tier to estimate changes in carbon stocks in mineral soils by land-use category (IPCC, 2019)

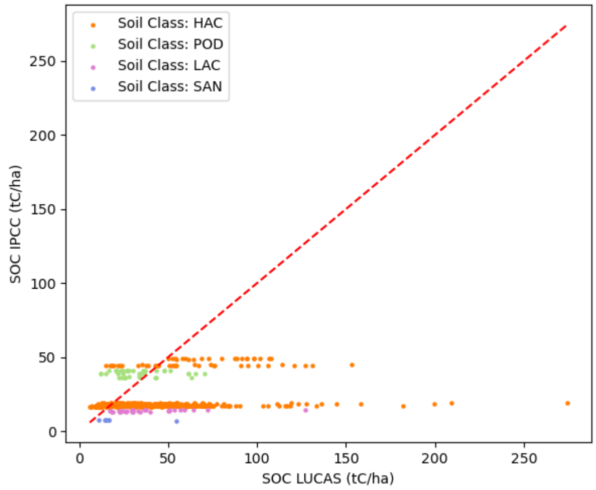
As soils are a 'key category' in the National GHG Inventory, our results highlight the importance of developing higher tier methods for future use in Portugal, such as Tier 2 or Tier 3.

II. The IPCC Tier 1 underestimated SOC Stocks affect only some soil types, some climate types and/or some land-uses;

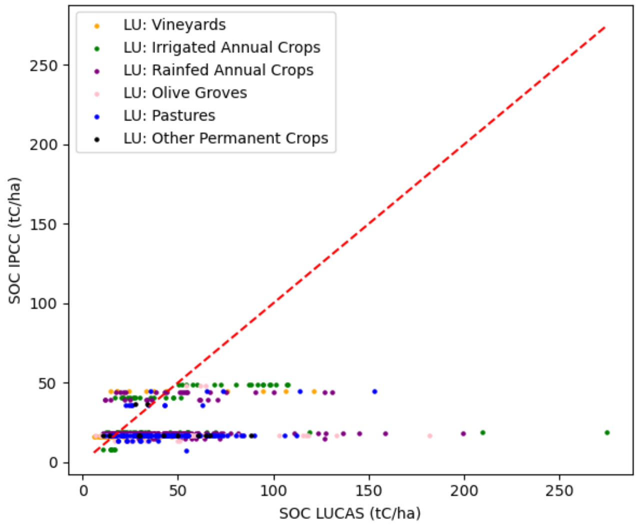
In an effort to understand possible reasons for the general underestimation by the IPCC, we tried to see if different patterns emerged for different soil, climate and land-use conditions. Figure 4-15 a) shows points classified by climate type, b) shows points classified by soil type and c) the same points classified by land-use.



a)



b)



c)

Figure 4-15 - SOC IPCC BCS vs. SOC LUCAS (2009, 2015, 2018), n = 578, classified by climate a), by soil class, b), and by land-use, c)

With the exception of Podzols, which seem to be centred on the diagonal, there is no obvious emerging pattern showing that a particular factor is able to justify the observed differences. This reinforces the observation above that a) SOC_{REF} defaults are not adequate to represent climate and soil types of Mainland Portugal; and/or b) the Stock Change Factors (F_{Lu}, F_{Mg} and/or F_{I}) do not properly represent the prevailing management conditions and options in the country.

Furthermore, Figure 4-15 highlight that: Although there might be issues with the map of Podzols in Portugal (Ramos, T. personal communication) Podzols are an exception in our results, producing average estimates comparable with LUCAS

i) Climate type appears to have a greater impact in determining SOC as a clear pattern is observed where humid climates convey higher SOC stocks;

ii) Soil type appears to be a less determinant factor in conveying SOC stocks as, for example, HAC soils appear both in the lower as well as upper SOC bands. Podzols are an exception to this as they drive SOC stocks up. Although issues with the classification of Podzols were identified - as it is likely not the most adequate soil classification for these sections of the country[13] - it is the only category where we obtain results cantered around the diagonal which are comparable with LUCAS.

iii) There is no SOC stock pattern related to land-use types alone.

iv) W1/HAC combination leads to higher SOC values, a result we had already previously highlighted.

v) The highest SOC values are obtained for irrigated annual crops in a warm temperate moist (W1) region, in HAC soils.

III. The method used to make LUCAS and IPCC compatible is overestimating LUCAS results

As described above (section 3.6) LUCAS data is not directly comparable to IPCC estimates and needs to be processed to enable this comparison. We considered that some of the conversion factors used to estimate missing data (e.g. soil bulk density) or to enable a more correct comparison (e.g. "correction" for a soil depth of 30cm) may be driving an overestimation of LUCAS data. As some of the provided 2018 LUCAS points have measured, rather than estimated, bulk density at 30cm depth. We may attempt to test this option by excluding all the points for which BD was estimated and plot our IPCC Baseline Scenario against LUCAS sampled points only for points in those conditions, n = 65 (Figure 4-16).

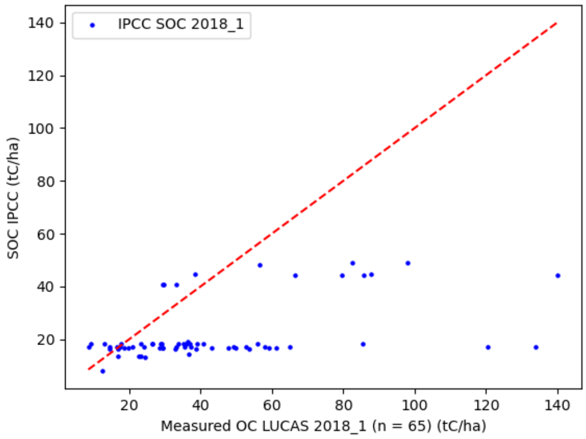


Figure 4-16 - SOC IPCC Baseline vs. SOC LUCAS (2018_1), n = 65.

As we may observe from Figure 4-16, the SOC values provided by the IPCC Baseline scenario mostly underestimate SOC stocks (83%) in comparison to the measured OC LUCAS values, i.e. a similar pattern to what was observed before.

The testing of the different hypotheses suggests that it is indeed the IPCC Tier 1 methodology that tends to underestimate SOC stocks in Mainland Portugal, indicating that IPCC's Stock change factors (SCFs) and the SOC_{REF} values may not adequately represent Portugal's case.

[13] We were informed, during the defense of this thesis, that the Podzol classification attributed to Portuguese soils is in fact incorrect (Ramos, T.)

Comparison with Morais et al. (2019)

Morais et al. (2019) developed an alternative method with a modified application of the RothC model to estimate global annual SOC stocks, for 43 LU classes (28 cropland, 16 forests and 1 grassland class) in 17,000 unique homogeneous territorial units, defined as a combination of soil type and texture, thermal zones, land cover and country. RothC was ran for 86 years and SOC stocks were calculated for each year at a 0-30 cm depth in tC ha^{-1}. To the resulting SOC trajectory, an exponential curve was fitted, with two parameters, from which could be obtained an input rate and a mineralisation rate (see equation (15) below). Estimations were computed for different cropland classes (such as wheat, maize, potatoes, tomatoes, etc), perennial classes (bananas, oranges, grapes, apples), forests and grasslands considering the application of different management practices: irrigation (rainfed or irrigated) and input (residues or no residues on field) with and without organic fertilization. SOC sequestration potentials for the effects of tillage were not considered in their assessment, since RothC does not consider tillage effects.

We identified three transitions from this work comparable to those of Morais et al. (2019), as shown in Table 4-6.

Table 4-6 – Transitions (this work) to be compared with LUs from Morais et al. (2019)

		This Work	Morais et al. (2019)		
Transition		Land-use (COS)	LU (Residues left on field)	Irrigated	Organic Fertilization
T2		Rainfed Annual Crops (CL1)	Barley, Maize, Rapeseed, Sorghum, Wheat	No	No
T2		Irrigated Annual Crops (CL2)	Barley, Maize, Rapeseed, Sorghum, Wheat	Yes	No
T3	T3A	Rainfed Annual Crops (CL1)	Barley, Maize, Rapeseed, Sorghum, Wheat	No	No
T3	T3A	Olive Groves (CL6), Other Permanent Crops (CL7)	Oranges, Grapes, Olives, Apples	Yes	No
T3	T3B	Irrigated Annual Crops (CL2)	Barley, Maize, Rapeseed, Sorghum, Wheat	Yes	No
T3	T3B	Olive Groves (CL6), Other Permanent Crops (CL7)	Oranges, Grapes, Olives, Apples	Yes	No

The choice to include only crops with residues left on field has to do with the fact that the "Medium" and "High" Input Stock Change Factor (F_I) considers, in addition to irrigation, practices such as production of high residue yielding crops, use of green manures, cover crops, improved vegetated fallows and/or frequent use of perennial grasses in annual crop rotations (See Table B-1).

These estimations, however, are not directly comparable since our results consider 20 years of application of the new land-use and land management practice and are presented in yearly values (tC ha^{-1} y^{-1}) following a linear model, while the final results of Morais et al. (2019) follow a non-linear curve over a 86-year period for estimating SOC at time t in each UHTU, described by

$$SOC_t = \frac{K}{\alpha}\,(1 - e^{-\alpha t}) + e^{-\alpha t} SOC_0, \tag{15}$$

where SOC_t is the SOC stock (t C ha) at time t, K is the C input to soil at time t, and α is the C mineralization rate. SOC is limited by an upper bound (asymptote) given by k/α, which corresponds to SOC “at equilibrium”.
Since K and α values per UHTU and LU were estimated by the authors of this paper, we may compare our emission/sequestration factor results with an annual sequestration value for each UHTU of interest. See section E of the Appendix for a detailed explanation of the method followed to obtain an annual emission from Morais et al. (2019). Note that the fundamental assumption for the method we have followed is that the final stock obtained after 86 years in Morais et al. (2019) is equivalent to the final stock considered by the IPCC.

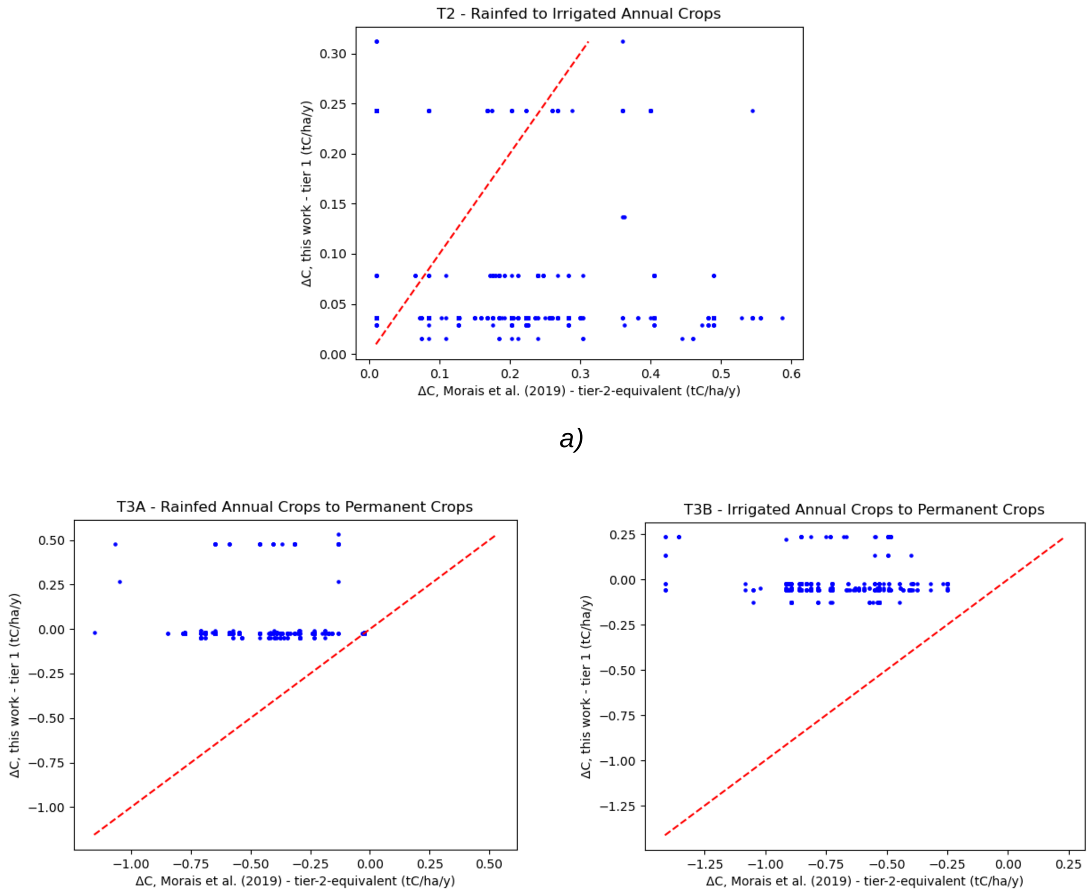
Generally, implementing irrigation and leaving residues on field in barley, maize, rapeseed, sorghum and wheat crops enhances SOC. This same tendency was observed in our estimations following the IPCC Tier 1 Methodology, whereby a transition from rainfed annual crops to irrigated annual crops (T2) delivers sequestration results. However, Morais et al. obtained an overall higher mean sequestration potential (0.18 tC ha^{-1} y^{-1}), twice more than the mean obtained with IPCC Tier 1 methodology (0.07 tC ha^{-1} y^{-1}).

Table 4-7 – Mean ΔC (tC ha^{-1} y^{-1}) Portugal obtained for each transition for this work and Morais et al. (2019)

Transition		This Work	Morais et al. (2019)
		Mean ΔC (tC ha^{-1} y^{-1})	
T2		0.07	0.18
T3	T3A	0.005	-0.5
	T3B	-0.03	-0.73

With Morais et al. estimated k and α, for Transition 3A (rainfed annual crops to perennial crops) and Transition 3B (irrigated annual crops to perennial crops), we obtain an overall scenario of C emission, with respective means of -0.50 and -0.73 of (emitted) tC ha^{-1} y^{-1}, for points in mainland Portugal. Following the IPCC Tier 1 Methodology, we obtain a positive but small mean sequestration value for T3A (0.005 tC ha^{-1} y^{-1}) and emission of C from T3B (-0.03 tC ha^{-1} y^{-1}).

This comparison shows that the results obtained with the Tier 1 Methodology are quantitatively different when compared to values obtained through a modelled approach. The IPCC Tier 1 tends to result in both lower emission and sequestration potentials of land-use and land management changes translated in transitions 2 and 3A and 3B (Figure 4-17), with the modelled approach showing greater variability in all transitions, with T3A and T3B results range by Morais et al. not including the results obtained in this work (Figure 4-18). Nevertheless, the tendencies of sequestration and emission are qualitatively similar in both works.

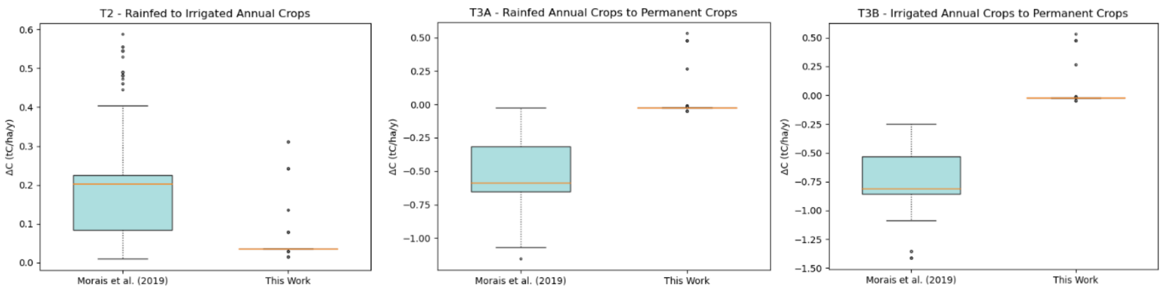


a)

b) *c)*

Figure 4-17 – dC in tC ha^{-1} y^{-1}, this work vs. Morais et al. (2019), a) T2, b) T3A, c) T3B

Additionally, in Morais et al. (2019), grasslands generally reached higher SOC levels than croplands due to “plant shoot and roots and animal C inputs to soils”. We obtained similar qualitative results in this matter, for our $SOC_{Baseline}$ estimations. Exceptionally, in Morais et al. (2019), for irrigated wheat and maize with residues left on field, higher stocks were obtained than for grassland, for certain regions of the world. In Portugal, specifically, irrigated maize with residues on field was estimated to provide higher SOC stocks when compared to an agricultural land-use of grassland being applied in the same region. This relationship was not observed for any region in Portugal when following the IPCC Tier 1, as $SOC_{Baseline}$ stocks were always greater for grasslands (with high intensity grazing) than for irrigated crops (which may also include residues left on field) when considering the same climate and soil type regions to apply that land-use/land management practice.



a) *b)* *c)*

Figure 4-18 – Variability of dC estimations, Morais et. al (2019) vs. this work, a) T2, b) T3A, c) T3B

5 Conclusions and Recommendations

This thesis applied the IPCC Tier 1 methodology to estimate SOC stocks and C sequestration/emission potentials for grassland and cropland in Mainland Portugal associated with some land-use and land management changes.

We began by mapping SOC_{REF} stocks, a reference scenario which represents conditions of no land-use or land-conversion. Here, we concluded that Northern regions of Portugal, where colder and more humid climate types and soils with high clay content prevail show greater SOC stocks. We then estimated SOC stocks in a Baseline scenario, $SOC_{Baseline}$, for some combinations of land-use and management practices, using the land-use from 2018 as a starting point.

We then set a series of transitions – Full to No-Till, Rainfed to Irrigated Annual crops, Annual to Permanent crops, and Poor Natural Grasslands to Improved Grasslands – to be applied for 20-year period. Emission/sequestration factors are obtained, per year, area and site, and transition. An estimation of the uncertainty of these emission/sequestration values was obtained with Monte Carlo Simulations, emphasizing how different soil/climate combinations may show great variability, illustrating the full spectrum of C emission or sequestration factors using the IPCC default factors.

By averaging ΔC_i values per sub-region (NUTS3) and multiplying by the areas available for application of each transition, we obtained an estimation of an overall national theoretical sequestration potential (tC y^{-1}), for Mainland Portugal. Transition 3 – annual crops to intensive permanent crops (such as orchards, vineyards, and other tree plantations) may result in scenarios of emission in the regions of Portugal such as Alto Alentejo and Lezíria do Tejo. This demonstrates that this transition of land-use in these areas may not be the most recommendable if soil C sequestration is the main goal. Transition 4 – natural poor grasslands to improved grasslands (with input enhancement and enhanced species variety) – provided the highest estimated sequestration potential, 1.43 $MtCO_2$ y^{-1}. It is important to recall that these are theoretical and maximum potentials. Actual potential would depend on numerous factors, including the capacity to mobilize farmers to adopt certain practices, but also market developments in agriculture, which may promote or hinder the adoption of the practices we studied.

Our assessment of the IPCC Adequacy, whereby we compared LUCAS in-situ sampled data (2009, 2015, 2018) with $SOC_{Baseline}$ estimations suggests that the IPCC Tier 1 methodology tends to underestimate SOC values in Mainland Portugal. Furthermore, our comparison with Morais et. al (2019) modelled estimates revealed that Tier 1 results in relatively lower sequestration and emission potentials. This emphasizes the need for the development of higher tier methods that accurately represent the context of Portugal, methodologies which may only be obtained if efforts are put into increasing in-situ measuring and improving standardization of sampling methods to do so.

We would like to acknowledge that there is space for improving the methods used well as our review of the literature. Here are some of the improvements which can be done moving forward:

- Improve literature review on the land-use and land management practices specifically chosen for our estimations of soil carbon sequestration to compare results;
- Reduce switch-over between software (From Excel to Python, from Python to Excel and from these two to QGIS) to improve our efficiency;
- Improve representation of CAP's agri-environment schemes by developing transition scenarios which represent the current land management practices being supported by CAP's Pillar II in Portugal; This would contribute to improving comprehension on the potential effects of the application of these practices and contribute to the main goals posed by N.Agroclima;
- Calculate $SOC_{Baseline}$ stocks in tC y^{-1} by obtaining and using the areas of the agricultural parcel correspondent to each site, providing a more detailed picture and closer approximation to a technical estimation of SOC stock;
- Test other land-use and land management transitions such as the use of cover crops or set-aside land;
- Critical review of the literature on which the stock change factors and SOC_{REF} values provided by the IPCC Tier 1 methodology are based to understand whether this literature contemplates in-situ data from Portugal and how well it is represented;

Our work on this thesis shows that there is a need for collecting in-situ data regarding soil's current conditions and biophysical constraints to enable the development of higher tier methods which may provide better estimates for Portugal's SOC stocks and soil C sequestration potentials. Enhancing the systematic collection of data on soil profiles – such as bulk density and organic carbon, at preferably 30cm depths - is essential if we aim to better represent Portugal's soils at a national scale. Such data may also be used as training and calibrating inputs for models, allowing us to improve our estimations and knowledge regarding what land management practices and land-use conversions are more beneficial in terms of soil C sequestration, according to local bio-physical constrains. Such knowledge could be essential to accurately inform policy makers and, if combined with a robust system of monitoring and verification, allow for the establishment of reliable carbon market mechanisms.

Furthermore, estimating and accounting for other GHG emissions (such as CH_4, N_2O) during land-use and land management changes is of high relevance. In fact, it is essential to not get stuck in a "carbon tunnel vision" since it is misleading to assess environmental benefits or climate mitigation strategies through carbon accounting only. A systems approach should be considered to assess the climate mitigation effects of practices that enhance soil carbon sequestration, though, for example, a full LCA (Life Cycle Assessment). A full assessment of water availability in the cases of transitions which include enhanced irrigation should be taken as well as an assessment of other possible effects related to climate change adaptation. We believe it would also be beneficial to estimate costs of mitigation options (such as cost of irrigation per tC sequestrated or opportunity cost per crop conversion – such as the opportunity cost of converting land-uses for annual crops to permanent crops), as this would increase our knowledge on the technical and economic feasibility of the different transitions as well as inform policymakers regarding funding and financial support needs of farmers in the case of application of such practices.

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Appendix

A. Data

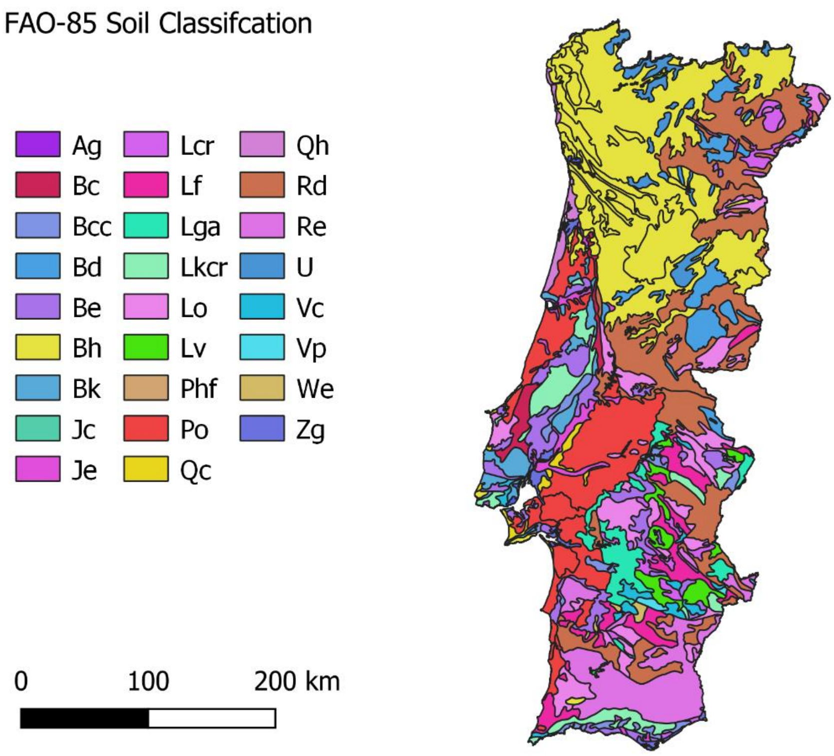

Figure A-1 - FAO-85 soil classification Mainland Portugal. Adapted from the European Soil Atlas (2005)

Table A-1 - FAO-85 soil classification for soil classes present in Portugal and conversion to IPCC soil class. Adapted from Batjes (2009)

FAO-85 SYMBOL	FAO-85 Class	IPCC Soil Class
Ag	Gleyic Acrisols	LAC/HAC
Bc	Chromic Cambisols	HAC
Bcc	Calcaro-chromic Cambisol	HAC
Bd	Dystric Cambisols	HAC
Be	Eutric Cambisol	HAC
Bh	Humic Cambisol	HAC
Bk	Calcic Cambisol	HAC
Jc	Calcaric Fluvisol	HAC
Je	Eutric Fluvisols	HAC
Lcr	Rhodo-chromic Luvisol	HAC
Lf	Ferric Luvisol	LAC
Lga	Albo-gleyic Luvisol	HAC
Lkcr	Rhodo-chromo-clacic Luvisol	HAC

(cont.)		
FAO-85 SYMBOL	**FAO-85 Class**	**IPCC Soil Class**
Lo	Orthic Luvisol	HAC
Lv	Vertic Luvisol	HAC
Phf	Ferro-humic Podzol	POD
Po	Orthic Podzols	POD
Qc	Cambic Arenosol	SAN
Qh	Haplic Arenosol	SAN
Rd	Dystric Regosol	HAC
Re	Eutric Regosol	HAC
U	Ranker	HAC
Vc	Chromic Vertisol	HAC
Vp	Pellic Vertisol	HAC
We	Eutric Planosol	HAC
Zg	Gleyic Solonchak	HAC

Figure A-2 - NUTS3-2013 classification, Mainland Portugal (COS/DGT)

B. IPCC Tier 1 methodology

Determination of SOC_{REF} and Standard Deviation (SD) for POD/W2 combination (unclassified by the IPCC), described, respectively, by

$$SOC_{REF_{POD/W2}} = \frac{1}{2} * \left(\frac{\mathrm{SOC}_{REF\ HAC/W2}}{\mathrm{SOC}_{REF\ HAC/W1}} + \frac{\mathrm{SOC}_{REF\ LAC/W2}}{\mathrm{SOC}_{REF\ LAC/W1}} \right) * SOC_{REF_{POD/W1,}} \quad (16)$$

where $SOC_{REF_{POD/W2}}$ is in tC ha^{-1} and $\mathrm{SOC}_{REF\ HAC/W2}, \mathrm{SOC}_{REF\ HAC/W1}, \mathrm{SOC}_{REF\ LAC/W2}, \mathrm{SOC}_{REF\ LAC/W1}$, $SOC_{REF_{POD/W1,}}$ represent, respectively, SOC_{REF} values in tC ha^{-1} for soil climate/combinations of HAC/W2, HAC/W1, LAC/W2, LAC/W1 and POD/W1, summarized in Table 3-6.

$$SD_{POD/W2} = \frac{1}{2} * \left(\frac{\mathrm{SD}_{HAC/W2}}{\mathrm{SD}_{HAC/W1}} + \frac{\mathrm{SD}_{LAC/W2}}{\mathrm{SD}_{LAC/W1}} \right) * SD_{POD/W1,} \quad (17)$$

where $SD_{POD/W2}$ is the standard deviation associated with IPCC's $SOC_{REF_{POD/W2}}$at 95% and for the soil/climate combination of POD/W2 and $\mathrm{SD}_{HAC/W2}, \mathrm{SD}_{HAC/W1}, \mathrm{SD}_{LAC/W2}, \mathrm{SD}_{LAC/W2}, \mathrm{SD}_{POD/W1}$ represent, respectively, standard deviation values of each respective SOC_{REF} for soil cl mate/combinations of HAC/W2, HAC/W1, LAC/W2, LAC/W1 and POD/W1, summarized in Table 3-6.

Table B-1 - Relative carbon stock change factors (SCFs) for cropland management (IPCC 2019, Table 5.5, Chapter 5)

TABLE 5.5 (UPDATED)							
RELATIVE CARBON STOCK CHANGE FACTORS (FLU, FMG, AND FI) (OVER 20 YEARS) FOR MANAGEMENT ACTIVITIES ON CROPLAND							
Factor value type	**Level**	**Temperature regime**	**Moisture regime[1]**	**IPCC defaults**	**Error[2,3]**	**SD (σ)**	**Description**
Land use[5] (F_{LU})	Long-term cultivated	Cool Temperate Boreal	Dry	0.77	14%	0.054	Represents area that has been converted from native conditions and continuously managed for predominantly annual crops over 50 yrs. Land-use factor has been estimated under a baseline condition of full tillage and nominal ('medium") carbon input levels. Input and tillage factors are also applied to estimate carbon stock changes, which includes changes from full tillage and medium input.
			Moist	0.7	12%	0.042	
		Warm Temperate	Dry	0.76	12%	0.046	
			Moist	0.69	16%	0.055	
		Tropical	Dry	0.92	13%	0.060	
			Moist/Wet	0.83	11%	0.046	
Land use[6] (F_{LU})	Paddy rice	All	Dry and Moist/Wet	1.35	4%	0.027	Long-term (> 20 year) annual cropping of wetlands (paddy rice). Can include double-cropping with non-flooded crops. For paddy rice, tillage and input factors are not used.
Land use[5] (F_{LU})	Perennial/ Tree Crop	Temperate/ Boreal	Dry and Moist	0.72	22%	0.079	Long-term perennial tree crops such as fruit and nut trees, coffee and cacao.
		Tropical	Dry and Moist/Wet	1.01	25%	0.126	
Land use (F_{LU})	Set aside (< 20 yrs)	Temperate/ Boreal and Tropical	Dry	0.93	11%	0.051	Represents temporary set aside of annually cropland (e.g., conservation reserves) or other idle cropland that has been revegetated with perennial grasses.
			Moist/Wet	0.82	17%	0.070	
		Tropical montane[44]	n/a	0.88	50%	0.220	
Tillage (F_{MG})	Full	All	Dry and Moist/Wet	1	n/a	n/a	Substantial soil disturbance with full inversion and/or frequent (within year) tillage operations. At planting time, little (e.g., <30%) of the surface is covered by residues.
Tillage[7] (F_{MG})	Reduced	Cool Temperate/ Boreal	Dry	0.98	5%	0.025	Primary and/or secondary tillage but with reduced soil disturbance (usually shallow and without full soil inversion). Normally leaves surface with >30% coverage by residues at planting.
			Moist	1.04	4%	0.021	
		Warm Temperate	Dry	0.99	3%	0.015	
			Moist	1.05	4%	0.021	
		Tropical	Dry	0.99	7%	0.035	
			Moist/Wet	1.04	7%	0.036	
Tillage[7] (F_{MG})	No-till	Cool Temperate/ Boreal	Dry	1.03	4%	0.021	Direct seeding without primary tillage, with only minimal soil disturbance in the seeding zone. Herbicides are typically used for weed control.
			Moist	1.09	4%	0.022	
		Warm Temperate	Dry	1.04	3%	0.016	
			Moist	1.1	4%	0.022	
		Tropical	Dry	1.04	7%	0.036	
			Moist/Wet	1.1	5%	0.028	
Input (F_I)	Low	Temperate/ Boreal	Dry	0.95	13%	0.062	Low residue return occurs when there is removal of residues (via collection or burning), frequent bare-fallowing, production of
			Moist	0.92	14%	0.064	

TABLE 5.5 (UPDATED)							
RELATIVE CARBON STOCK CHANGE FACTORS (FLU, FMG, AND FI) (OVER 20 YEARS) FOR MANAGEMENT ACTIVITIES ON CROPLAND							
Factor value type	**Level**	**Temperature regime**	**Moisture regime[1]**	**IPCC defaults**	**Error[2,3]**	**SD (σ)**	**Description**
		Tropical	Dry	0.95	13%	0.062	crops yielding low residues (e.g., vegetables, tobacco, cotton), no mineral fertilization or N-fixing crops.
			Moist/ Wet	0.92	14%	0.064	
		Tropical montane[4]	n/a	0.94	50%	0.235	
Input $^{(F_I)}$	Medium	All	Dry and Moist/ Wet	1	n/a	n/a	Representative for annual cropping with cereals where all crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g., manure) is added. Also requires mineral fertilization or N-fixing crop in rotation.
Input $^{(F_I)}$	High without manure	Temperate/ Boreal and Tropical	Dry	1.04	13%	0.068	Represents significantly greater crop residue inputs over medium C input cropping systems due to additional practices, such as production of high residue yielding crops, use of green manures, cover crops, improved vegetated fallows, irrigation, frequent use of perennial grasses in annual crop rotations, but without manure applied (see row below).
			Moist/ Wet	1.11	10%	0.056	
		Tropical montane[4]	n/a	1.08	50%	0.270	
Input $^{(F_I)}$	High with manure	Temperate/ Boreal and Tropical	Dry	1.37	12%	0.082	Represents significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.
			Moist/ Wet	1.44	13%	0.094	
		Tropical montane[4]	n/a	1.41	50%	0.353	

Notes: Long-term cultivation, perennial crops paddy rice and tillage management factors were derived using methods provided in Annex 5A1.

[1]Where data were sufficient, separate values were determined for temperate and tropical temperature regimes; and dry, moist, and wet moisture regimes. Temperate and tropical zones correspond to those defined in Chapter 3; wet moisture regime corresponds to the combined moist and wet zones in the tropics and moist zone in temperate regions.

[2]± two standard deviations, expressed as a percent of the mean; where sufficient studies were not available for a statistical analysis to derive a default, uncertainty was assumed to be ± 50% based on expert opinion. NA denotes 'Not Applicable', where factor values constitute defined reference values, and the uncertainties are reflected in the reference C stocks and stock change factors for land use.

[3] This error range does not include potential systematic error due to small sample sizes that may not be representative of the true impact for all regions of the world.

[4]There were not enough studies to estimate some of the stock change factors for mineral soils in the tropical montane climate region. As an approximation, the average stock change between the temperate and tropical regions was used to approximate the stock change for the tropical montane climate.

Sources:[5] The following references used for land-use factors (other than paddy rice): Aborisade and Aweto, 1990; Adachi *et al.*, 2006; Agbenin and Goladi, 1997; Aina, 1979; Alcantara *et al.*, 2004; Allen, 1985; An *et al.*, 2003; Ashagrie *et al.*, 2005; Assad *et al.*, 2013; Aweto, 1981; Aweto and Ayuba, 1988; Aweto and Ayuba, 1993; Aweto and Ishola, 1994; Ayanaba *et al.*, 1976; Banaticla and Lasco, 2006; Bashkin and Binkley, 1998; Batlle-Bayer *et al.*, 2010; Bautista-Cruz and del Castillo, 2005; Berhongaray *et al.*, 2013; Bernardi *et al.*, 2007; Bernhardreversat, 1988; Berthrong *et al.*, 2012; Bertol and Santos, 1995; Beyer, 1994; Binkley *et al.*, 2004; Binkley and Resh, 1999; Bonde *et al.*, 1992; Bowman and Anderson, 2002; Brand and Pfund, 1998; Brown and Lugo, 1990; Bruun *et al.*, 2006; Burke *et al.*, 1995; Burke *et al.*, 1995; Buschbacher *et al.*, 1988; Buschiazzo *et al.*, 1998; Buyanovksy *et al.*, 1987; Cadisch *et al.*, 1996; Cai *et al.*, 2008; Cambardella and Elliott, 1994; Cambardella and Elliott, 1992; Campos *et al.*, 2007; Cao *et al.*, 2004; Carvalho *et al.*, 2009; Carvalho *et al.*, 2009; Cerri *et al.*, 1991; Cerri *et al.*, 2003; Cerri *et al.*, 2007; Chan, 1997; Chandran *et al.*, 2009; Chen *et al.*, 2007; Chen, 2006; Chia *et al.*, 2017; Chidumayo and Kwibisa, 2003; Chiti *et al.*, 2014; Chone *et al.*, 1991; Cleveland *et al.*, 2003; Collins *et al.*, 1999; Conant *et al.*, 2001; Conti *et al.*, 2014; Cook *et al.*, 2014; Corazza *et al.*, 1999; D'Annunzio *et al.*, 2008; da Silva-Junior *et al.*, 2009; Dai *et al.*, 2008; Dai *et al.*, 2008; Dalal *et al.*, 2005; Dalal and Mayer, 1986; Dawoe *et al.*, 2014; de Blecourt *et al.*, 2013; de Camargo *et al.*, 1999; de Freitas *et al.*, 2000; de Koning *et al.*, 2003; de Moraes *et al.*, 2002; de Moraes *et al.*, 1996; de Neergaard *et al.*, 2008; Dechert *et al.*, 2004; Delelegn *et al.*, 2017; Denef *et al.*, 2007; Desjardins *et al.*, 1994; Desjardins *et al.*, 2004; Detwiler, 1986; Eaton and Lawrence, 2009; Eclesia *et al.*, 2012; Eden *et al.*, 1990; Ekanade, 1991; Elliott *et al.*, 1991; Elmore and Asner, 2006; England *et al.*, 2016; Epron *et al.*, 2009; Erickson *et al.*, 2001; Fabrizzi *et al.*, 2009; Farley *et al.*, 2004; Feldpausch *et al.*, 2004; Feller *et al.*, 2001; Fernandes *et al.*, 2002; Fernandez *et al.*, 2012; Fisher *et al.*, 1994; Follett *et al.*, 1997; Freibauer, 1996; Freixo *et al.*, 2002; Fu *et al.*, 2000; Fu *et al.*, 2001;

Table B-2 – Relative carbon stock change factors (SCFs) for grassland management (IPCC 2019, Table 6.2, Chapter 6)

TABLE 6.2 (UPDATED) RELATIVE STOCK CHANGE FACTORS FOR GRASSLAND MANAGEMENT					
Factor	**Level**	**Climate regime**	**IPCC default**	**Error [1,2]**	**Definition**
Land use (F_{LU})	All	All	1.0	NA	All native and/or permanent grassland in a nominal condition is assigned a land-use factor of 1.
Management (F_{MG})	Nominally managed (non – degraded)	All	1.0	NA	Represents low or medium intensity grazing regimes, in addition to periodic cutting and removal of above-ground vegetation, without significant management improvements.
Management (F_{MG})	High Intensity Grazing[3]	All	0.90	±8%	Represents high intensity grazing systems (or cutting and removal of vegetation) with shifts in vegetation composition and possibly productivity but is not severely degraded[4].
Management (F_{MG})	Severely degraded	All	0.7	±40%	Implies major long-term loss of productivity and vegetation cover, due to severe mechanical damage to the vegetation and/or severe soil erosion.
Management (F_{MG})	Improved grassland	Temperate/ Boreal	1.14	±11%	Represents grassland which is sustainably managed with light to moderate grazing pressure (or cutting and removal of vegetation) and that receive at least one improvement (e.g., fertilization, species improvement, irrigation).
		Tropical	1.17	±9%	
		Tropical Montane[5]	1.16	±40%	
Input (F_I)	Medium	All	1.0	NA	Applies to improved grassland where no additional management inputs have been used.
Input (F_I)	High	All	1.11	±7%	Applies to improved grassland where one or more additional management inputs/improvements have been used (beyond that required to be classified as improved grassland).

Management factors were derived using methods and studies provided in Annex 6A1. The basis for the other factors is described in the *2006 IPCC Guidelines*. Source:

[3] The bibliography for the following references used for management factor can be found in Annex 6A.1:
Cao *et al.*, 2013; Ding *et al.*, 2014; Du *et al.*, 2017; Frank *et al.*, 1995; Franzluebbers and Stuedemann, 2009; Gao *et al.*, 2018; Gao *et al.*, 2007; Gillard, 1969; Han *et al.*, 2008; He *et al.*, 2008; Ingram *et al.*, 2008; Kioko *et al.*, 2012; Kölbl *et al.*, 2011; Li *et al.*, 2008; Liu *et al.*, 2012; Manley *et al.*, 1995; Martinsen *et al.*, 2011; Potter *et al.*, 2001; Qi *et al.*, 2010; Rutherford and Powrie, 2011; Schulz *et al.*, 2016; Schuman *et al.*, 1999; Segoli *et al.*, 2015; Smoliak *et al.*, 1972; Sun *et al.*, 2011; Talore *et al.*, 2016; Teague *et al.*, 2011; Wang *et al.*, 2017; Wei *et al.*, 2011; Xu *et al.*, 2014; Yanfen *et al.*, 1998; Zhang *et al.*, 2018; Zhou *et al.*, 2010; Zou *et al.*, 2015

Notes:

[1] ± two standard deviations, expressed as a percent of the mean; where sufficient studies were not available for a statistical analysis a default, based on expert judgement, of ± 40% is used as a measure of the error. NA denotes 'Not Applicable', for factor values that constitute reference values or nominal practices for the input or management classes.

[2] This error range does not include potential systematic error due to small sample sizes that may not be representative of the true impact for all regions of the world.

[4] High intensity grazing may be moderately degraded, but do not represent excessive grazing intensity that leads to severe grassland degradation.

[5] There were not enough studies to estimate stock change factors for mineral soils in the tropical montane climate region. As an approximation, the average stock change between the temperate and tropical regions was used to approximate the stock change for the tropical montane climate.

C. National sequestration potential

Table C-1 - Area of land occupied by temporary crops (ha) by location (NUTS - 2013), type (temporary crops) and area classes (crop); 10-yearly (INE, 2019)

Data reference period	NUTS - 2013	Code	Total (ha)	Cereals for grain (ha)	Pulses (ha)	Temporary Grassland (ha)	Forage crops (ha)	Potato (ha)	Industrial Crops (ha)	Horticultural crops (ha)	Flowers and ornamental plants (ha)	Other temporary crops (ha)
2019	Portugal	PT	888384	234599	18696	120576	433044	13383	10692	51996	1922	3477
	Continente	1	843477	234530	18666	105802	406264	12586	10507	50509	1828	2786
	Alto Minho	111	11226	3160	121	1320	6147	288	8	105	62	15
	Cávado	112	28190	3765	108	630	22676	247	22	642	78	22
	Ave	119	16293	3096	89	908	11636	165	35	295	63	5
	Área Metropolitana do Porto	11A	32814	3346	82	275	27104	438	16	1455	78	20
	Alto Tâmega	11B	14600	7908	59	1871	3300	1299	3	128	7	25
	Tâmega e Sousa	11C	10885	3817	182	762	5467	283	31	269	63	11
	Douro	11D	5859	1305	169	501	2973	593	13	289	10	6
	Terras de Trás-os-Montes	11E	31241	11854	1103	573	16731	478	36	452	6	9
	Oeste	16B	23967	3453	250	1280	9303	1495	86	7389	46	664
	Região de Aveiro	16D	19619	6009	307	210	11165	612	26	1166	30	93
	Região de Coimbra	16E	26162	14405	375	804	8357	654	32	1465	30	40
	Região de Leiria	16F	6490	2223	210	362	2990	112	4	530	37	22
	Viseu Dão Lafões	16G	12314	3653	332	1427	6110	560	15	194	11	11
	Beira Baixa	16H	22346	2324	982	3223	15650	28	20	100	2	16
	Médio Tejo	16I	11481	3503	251	531	6459	86	84	551	6	11
	Beiras e Serra da Estrela	16J	49508	10752	571	5909	31240	713	36	202	7	78
	Área Metropolitana de Lisboa	170	34812	9349	184	1521	13637	1702	242	7749	307	122
	Alentejo Litoral	181	68247	16567	2321	11764	33229	703	64	2481	537	580
	Baixo Alentejo	184	150201	60988	7182	26235	46543	62	6216	2830	18	126
	Lezíria do Tejo	185	77228	33718	628	4057	18264	1949	1117	16851	143	501
	Alto Alentejo	186	68334	10395	1381	16337	36719	28	896	2380	4	194
	Alentejo Central	187	109541	16343	1673	23642	64404	9	1357	2072	4	37
	Algarve	150	12120	2596	106	1659	6158	83	148	915	276	178

Table C-2 - Area of land occupied by grasslands and permanent pastures (ha) by location (NUTS-2013) and type; 10-yearly (INE, 2019)

				On clear ground			Under forest covers			Under permanent crops			Non-Productive in Basic Payment Scheme (BPS)
Data reference period	**NUTS3 - 2013**	**Code**	**Total (ha)**	**Total (ha)**	**Spontaneous improved and sown (ha)**	**Poor (ha)**	**Total (ha)**	**Spontaneous improved and sown (ha)**	**Poor (ha)**	**Total (ha)**	**Spontaneous improved and sown (ha)**	**Poor (ha)**	**Total (ha)**
2019	**Alto Minho**	111	54561	42080	5739	36341	11175	23	11152	125	72	53	1182
	Cávado	112	8261	7458	1769	5689	69	6	62	43	42	1	691
	Ave	119	24112	22554	4730	17824	844	83	761	57	52	4	657
	Área Metropolitana do Porto	11A	4368	4143	1045	3098	12	6	6	18	11	6	195
	Alto Tâmega	11B	71434	70159	17738	52420	143	55	88	15	14	1	1117
	Tâmega e Sousa	11C	11431	10927	2771	8156	63	15	47	55	47	8	385
	Douro	11D	23044	21555	4957	16599	180	16	164	47	13	35	1261
	Terras de Trás-os-Montes	11E	45168	37720	27513	10207	1211	467	744	8	6	2	6229
	Oeste	16B	7727	5035	2535	2501	2335	38	2296	26	10	16	331
	Região de Aveiro	16D	2086	1917	1445	473	7	4	3	4	3	1	157
	Região de Coimbra	16E	5054	4056	2376	1680	247	6	241	202	74	128	549
	Região de Leiria	16F	7069	6363	1582	4781	163	27	137	456	112	344	87
	Viseu Dão Lafões	16G	11744	11320	6062	5258	67	16	51	43	27	15	315
	Beira Baixa	16H	111043	69076	26424	42652	31738	14343	17395	3986	2001	1985	6243
	Médio Tejo	16I	11736	5782	2025	3756	4639	421	4218	1186	230	956	130
	Beiras e Serra da Estrela	16J	111988	103243	23621	79622	4890	705	4185	1138	576	562	2716
	Área Metropolitana de Lisboa	170	35837	17416	7518	9898	16748	4521	12226	723	401	322	951
	Alentejo Litoral	181	194921	86577	36134	50444	97315	19339	77976	1940	864	1076	9089
	Baixo Alentejo	184	328698	183726	32752	150974	128920	28994	99926	7926	241	7685	8125
	Lezíria do Tejo	185	88571	28691	11263	17428	53586	12815	40771	2442	316	2126	3851
	Alto Alentejo	186	341080	123914	22420	101494	203789	39117	164673	10492	1052	9440	2885
	Alentejo Central	187	478321	181228	66782	114446	275776	69431	206345	12645	2141	10504	8672
	Algarve	150	25545	18549	4108	14441	3886	305	3581	262	37	224	2849

Table C-3 - Irrigated areas per NUTS3 - 2013 (%) (INE, 2019)

		Irrigated Area (%)
NUTS3 - 2013	**Code**	**2019**
Alto Minho	111	21.01
Cávado	112	59.88
Ave	119	42.41
Área Metropolitana do Porto	11A	71.29
Alto Tâmega	11B	14.92
Tâmega e Sousa	11C	52.96
Douro	11D	12.33
Terras de Trás-os-Montes	11E	5.33
Oeste	16B	28.90
Região de Aveiro	16D	56.18
Região de Coimbra	16E	52.83
Região de Leiria	16F	21.88
Viseu Dão Lafões	16G	37.39
Beira Baixa	16H	13.38
Médio Tejo	16I	16.08
Beiras e Serra da Estrela	16J	14.97
Área Metropolitana de Lisboa	170	32.94
Alentejo Litoral	181	11.09
Baixo Alentejo	184	16.45
Lezíria do Tejo	185	33.46
Alto Alentejo	186	7.47
Alentejo Central	187	7.19
Algarve	150	22.52

Table C-4 - Total area per transition per NUTS3 - 2013 (ha) (INE, 2019)

	Total Area (ha)				
NUTS3 - 2013	**T1**	**T2**	**T3A**	**T3B**	**T4**
Alentejo Central	85,899	79,723	79,723	6,176	106,217
Alentejo Litoral	56,482	50,218	50,218	6,264	44,850
Algarve	10,460	8,104	8,104	2,356	11,189
Alto Alentejo	51,997	48,113	48,113	3,884	93,912
Alto Minho	9,906	7,825	7,825	2,081	28,706
Alto Tâmega	12,729	10,830	10,830	1,899	44,599
Ave	15,384	8,860	8,860	6,524	10,265
Baixo Alentejo	123,965	103,573	103,573	20,392	126,139
Beira Baixa	19,122	16,563	16,563	2,559	36,945
Beiras e Serra da Estrela	43,599	37,072	37,072	6,527	67,703
Cávado	27,560	11,057	11,057	16,503	2,282
Douro	5,358	4,697	4,697	661	14,552
Lezíria do Tejo	73,171	48,688	48,688	24,483	11,597
Médio Tejo	10,951	9,190	9,190	1,761	3,152

	Total Area (ha)				
NUTS3 - 2013	**T1**	**T2**	**T3A**	**T3B**	**T4**
Oeste	22,686	16,130	16,130	6,556	1,778
Região de Aveiro	19,408	8,505	8,505	10,903	207
Região de Coimbra	25,358	11,961	11,961	13,397	792
Região de Leiria	6,128	4,787	4,787	1,341	3,735
Terras de Trás-os-Montes	30,669	29,034	29,034	1,635	9,663
Tâmega e Sousa	10,123	4,762	4,762	5,361	3,837
Viseu Dão Lafões	10,886	6,816	6,816	4,070	3,292
Área Metropolitana de Lisboa	33,292	22,326	22,326	10,966	6,638
Área Metropolitana do Porto	32,539	9,342	9,342	23,197	889
Total	737,672	558,176	558,176	179,496	632,939

D. Results appendix

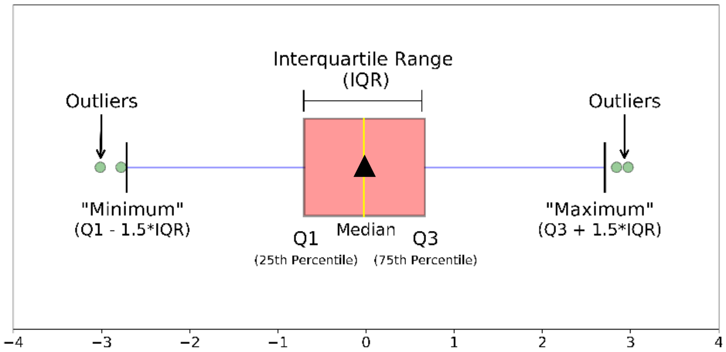

Figure D-1 - Elements of a boxplot (Understanding Boxplots, 2019)

The boxplots shown in section "Uncertainty of estimates" of this dissertation were obtained resourcing to 'Matplotlib', an open-source Python library. Each boxplot is standardized and displays the distribution of the data based on its five-number scenario: "minimum" first quartile [Q1], median, third quartile [Q3] and "maximum". Outliers and their values are also represented (Figure D-1). For each boxplot, we may obtain:

- First Quartile, Q1: -0.6745σ
- Third Quartile, Q3: +0.6745σ,
- IQR: Q3-Q1 (where 50% of the values lie)
- "maximum": 2.698σ
- "minimum": -2.698σ
- outliers: > 2.698σ or < - 2.698σ
- triangle: mean

Table D-1 - $\overline{\Delta C}$ (tC y^{-1}) per NUTS3 per transition

	$\overline{\Delta C}$ (tC y^{-1})				
NUTS3	**T1[14]**	**T2**	**T3A**	**T3B**	**T4**
Alentejo Central	3,118.70	2,874.05	-1,766.79	-378.02	47,407.44
Alentejo Litoral	3,147.82	2,541.30	-1,562.23	-656.79	24,282.52
Algarve	431.63	331.23	-118.98	-167.67	4,984.06
Alto Alentejo	2,020.83	1,844.57	-1,133.92	-243.83	43,192.75
Alto Minho	2,262.01	1,900.48	3,734.85	464.71	39,051.66
Alto Tâmega	2,018.10	1,807.68	3,151.85	325.85	54,011.10
Ave	3,667.55	2,151.83	4,228.82	1,529.52	12,640.11
Baixo Alentejo	4,422.79	3,685.10	-2,265.36	-1,170.88	54,594.92
Beira Baixa	979.38	948.42	481.49	-147.72	16,199.71
Beiras e Serra da Estrela	2,094.16	1,767.85	158.66	-188.10	44,102.82
Cávado	6,297.21	2,616.43	5,141.85	3,684.84	3,073.88
Douro	658.30	505.68	704.12	99.51	14,539.84
Lezíria do Tejo	3,185.55	2,163.98	-1,330.28	-1,634.91	7,525.61
Médio Tejo	669.21	645.43	425.90	-130.74	1,778.02
Oeste	992.90	693.16	-299.77	-464.87	804.53
Região de Aveiro	2,318.08	1,280.98	1,899.31	512.77	109.34
Região de Coimbra	2,149.16	1,094.87	1,062.68	-461.67	656.59
Região de Leiria	548.14	457.88	456.93	-78.84	3,142.00
Terras de Trás-os-Montes	1,708.24	1,661.02	817.57	-29.55	5,196.68
Tâmega e Sousa	2,362.24	1,156.56	2,272.89	1,256.82	4,883.24
Viseu Dão Lafões	1,917.74	1,073.29	1,843.82	765.68	3,234.97
Área Metropolitana de Lisboa	1,757.03	1,047.14	-643.71	-1,036.64	3,598.52
Área Metropolitana do Porto	7,722.79	2,268.97	4,459.02	5,292.90	881.56
Total (tC y^{-1})	**56,449.53**	**36,517.89**	**21,718.70**	**7,142.37**	**389,891.88**
Total (MtC y^{-1})	**0.06**	**0.04**	**0.02**	**0.01**	**0.39**
Total (MtCO_2 y^{-1})	**0.21**	**0.13**	**0.08**	**0.03**	**1.43**

[14] When we calculate a maximum national sequestration potential for CL1 and CL2 in Transition 1 separately, we obtain respectively, 0.13 MtCO_2 y^{-1} and 0.08 MtCO_2 y^{-1}.

E. Comparison with Morais et al. (2019)

To obtain early sequestration factors per POINT_ID, per UHTU, the following steps were taken:

- Extraction of S3 File - Unique Homogeneous Territorial Unit map (.TIF) - and S4 File - Map results UHTU scale (.xlsx) -, provided by Morais et al. 2019 as supportive elements of the article;
- Extracting UHTU values for each POINT_ID in each transition, following a spatial analysis with QGIS 3.0. Points which were not attributed an UHTU were excluded from further assessments;
- On Excel, obtaining a mean k/mineralization rate value per UHTU and aggregated LU (see Table 4-6);
- Calculating an early emission/sequestration factor per POINT_ID, described by

$$\Delta C = \frac{\overline{\frac{K_{final}}{\alpha_{final}}} - \overline{\frac{K_{baseline}}{\alpha_{baseline}}}}{20}, \qquad (18)$$

  where ΔC is the emission/sequestration factor in tC ha^{-1} y^{-1}, $\overline{\frac{K_{final}}{\alpha_{final}}}$ is the mean SOC, at equilibrium, 20 years after LU change, in tC ha^{-1}, $\overline{\frac{K_{baseline}}{\alpha_{baseline}}}$ is the mean initial SOC, at equilibrium, in tC ha^{-1}.
- Lastly, we obtained a mean national sequestration value for each transition for Morais et. al (2019), to be then compared with a mean/sequestration value for each transition from this work.