Universitat Autònoma de Barcelona

ASSESMENT OF THE ROLE OF MEDITERRANEAN AGRICULTURE AS A CARBON SINK AND DIAGNOSIS OF CLIMATE CHANGE IMPACTS: A BASELINE FOR EXPLORING ADAPTATION AND MITIGATION STRATEGIES

Inmaculada Funes Mesa

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Abstract

Agriculture is the human activity most severely affected by climate change, and, at present, it is heavily impacted in the Mediterranean Basin. However, carbon sequestration and storage in woody biomass and crop soils could become important tools in the fight against climate change in the Mediterranean.

The main objective of this thesis is to generate empirical knowledge that will serve as a baseline to test land use and agricultural management as strategies for adaptation and mitigation of climate change. A reliable evaluation of carbon stock in agriculture would be a useful baseline to quantify its spatial and temporal variability and gain a better understanding of the carbon cycle. Furthermore, assessing how climate is expected to affect crops is extremely useful for stakeholders, who can act at the local/regional scale to make agriculture more resilient and enhance food security. The specific objectives of this thesis, corresponding to Chapters 2, 3 and 4, are: i) to assess carbon stocks of Mediterranean woody crop biomass through crop- and site-specific models at the regional level; ii) to estimate soil organic carbon (SOC) stocks in agriculture, assessing the importance of their drivers and seeking to understand their spatial distribution; and iii) to diagnose climate change impacts on net hydric needs (NHN) and phenology of crops and other agroclimatic parameters at the basin and the sub-basin scale.

The results of the first study (Chapter 2) offer spatial estimates of total biomass carbon stock on woody cropland in Catalonia (NE Spain) of 5.48 Tg C, with an average value of 16.44 ± 0.18 Mg C/ha. During the 2010s, although in general the area covered by woody crops showed an annual decrease of 2.8%, carbon stocks in biomass of woody crops increased (+0.17 Tg C/year) due to growth of remaining woody cropland. The second study (Chapter 3) generated spatial estimates of total SOC stocks under agriculture in Catalonia at the topsoil level (0-30 cm) of 47.9 Tg C, with an average value of 48.8 ± 8.9 Mg C/ha. While topsoil variation of SOC stocks depended mainly on climate, soil texture and agricultural variables, subsoil (30-100 cm) SOC stock were principally dependent on soil attributes (soil texture, clay content, soil type or depth to bedrock). Modeling revealed that the relationship between SOC stocks and drivers varied spatially. According to the results of the last study (Chapter 4), NHN are expected to increase from 0.1% to 6.7% in the three basins of Catalonia studied, although dynamics will be different for each basin and, in general, trends vary from crop to crop. Moreover, phenological changes could represent a greater constraint for crop productivity. The number of frost days will decrease (from −0.1 days in March to −8.7 days in April) in the three basins, while extremely hot days will increase (from +0.3 days in July to +3.8 days in August). Growth cycles will begin earlier (from −1 days to −12 days for crops with a base temperature of 10 °C) and will be shorter (from −8 days to −27 days). Therefore, the impacts assessed in this study, together with the forecasted depletion of water sources in the study area, could result in significant limitations for crops if adaptive strategies beyond irrigation and growing cycle issues are not applied. In summary, this thesis provides spatial estimates of carbon stocks of agriculture in Catalonia and a diagnosis of the main climate change impacts on major crops in three representative basins of the Northwestern Mediterranean. All the empirical knowledge obtained can make a significant contribution to the tasks of evaluating the carbon consequences of agricultural practices and management and assessing adaptation of crops to climate change at the landscape level for different land and agricultural management scenarios, assisting stakeholders and policy makers.

Resum

La agricultura és l'activitat humana més afectada pel canvi climàtic, i, actualment, està fortament impactada a la conca Mediterrània. No obstant això, el segrest i emmagatzematge de carboni a la biomassa de cultius llenyosos i sòls agrícoles podria ser considerable a l'hora de combatre el canvi climàtic a la Mediterrània.

El principal objectiu d'aquesta tesi és generar coneixement empíric que serveixi de base per a simular estratègies de gestió d'usos de sòl i practiques agrícoles per l'adaptació i mitigació del canvi climàtic. Una avaluació fiable de les existències de carboni agrícoles suposa una línia de base molt útil per a quantificar la seva variabilitat espacial i temporal per comprendre millor el cicle del carboni i ajudar en la presa de decisions de les polítiques d'adaptació i mitigació a escala local i regional. D'altra banda, avaluar com s'espera que el clima afecti als cultius és extremadament útil per als diferents actors del territori, que són els que poden proposar i executar estratègies d'adaptació i mitigació a escala local i/o regional per fer possible una agricultura més resilient als canvis i millorar la seguretat alimentaria. Els objectius específics d'aquesta tesi, corresponents als capítols 2, 3 y 4, són: i) avaluar els estocs de carboni de la biomassa dels cultius llenyosos mediterranis a partir de models específics per cada zona i tipus de cultiu a escala regional, ii) estimar els estocs de carboni orgànic en sòls (COS) agrícoles, avaluar la importància de les variables explicatives i entendre els patrons espacials dels estocs de COS i iii) fer una diagnosi dels impactes del canvi climàtic en les necessitats hídriques netes (NHN) i fenologia dels cultius i altres paràmetres agroclimàtics a escala de conca i subconca.

Els resultats del primer treball (Capítol 2) ofereixen estimacions espacials del total del estoc de carboni en la biomassa de cultius llenyosos a Catalunya d'uns 5.48 Tg C, presentant un valor mitjà de 16.44 ± 0.18 Mg C/ha. Per la dècada dels 2010, i tot i que en general l'àrea ocupada pels cultius llenyosos es va reduir anualment un 2.8%, els estocs de carboni a la biomassa de cultius llenyosos van augmentar (+0.17 Tg C/any) degut al creixement en aquelles àrees on no hi va haver canvis d'ús de sòl. El segon treball (Capítol 3) va generar una estimació espacial dels estocs de COS superficials (0-30 cm) dels sòls agrícoles de Catalunya d'uns 47.9 Tg C, presentant un

valor mitjà de 48.8 ± 8.9 Mg C/ha. A més, mentre que la variació dels estocs de COS superficials va dependre principalment del clima, la textura del sòl i altres variables agrícoles, els estocs de COS de la capa subterrània (30-100 cm) van dependre principalment dels atributs del sòl. Els models espacials van revelar que la relació entre els estocs de COS i les seves variables explicatives variaven geogràficament. Els resultats de l'últim estudi de la tesis (Capítol 4) destaca l'augment generalitzat de les NHN del 0.1% fins al 6.7% que es produiria en les tres conques de Catalunya estudiades, tot i que les dinàmiques són diferents per les tres conques i, en general, aquestes tendències variaven entre cultius. A més, els canvis fenològics podrien representar una gran restricció per la producció agrícola. El nombre de dies de gelades decreixerà (de -0.1 dies al març fins a -8.7 dies a l'abril) en les tres conques, mentre que els dies extremadament càlids podria incrementar-se (de +0.3 dies al juliol fins a +3.8 dies a l'agost). El cicle de creixement dels cultius podria avançar-se (de -1 dies fins a -12 dies per a cultius amb temperatura base de 10ºC) i escurçar-se (de -8 dies fins a -27 dies). D'aquesta manera, els impactes avaluats en aquest treball, juntament amb el predit esgotament dels recursos hídrics a la zona d'estudi, podrien resultar en limitacions significatives per als cultius si no s'apliquen estratègies d'adaptació més enllà del reg i no s'enfronten els problemes en el cicle de creixement dels cultius.

En general, aquesta tesi aporta estimacions espacials dels estocs de carboni de la agricultura a Catalunya i una diagnosi dels principals impactes del canvi climàtic en els cultius majoritaris de tres conques representatives del nord-est Mediterrani. Tot el coneixement empíric obtingut en aquesta tesi pot contribuir significativament a avaluar les conseqüències en termes de carboni de la practiques i la gestió agrícola i a avaluar l'adaptació dels cultius al canvi climàtic a escala de paisatge per a diferents escenaris de gestió agrícola i territorial, oferint assistència a responsables polítics i actors del territori.

Resumen

La agricultura es la actividad humana más afectada por el cambio climático, y, actualmente, es impactada fuertemente en la cuenca del Mediterráneo. Sin embargo, el secuestro y almacenaje de carbono en la biomasa de cultivos leñosos y los suelos agrícolas podría ser considerable a la hora de combatir el cambio climático en el Mediterráneo.

El principal objetivo de esta tesis es generar conocimiento empírico que sirva de base para simular estrategias de gestión de usos de suelo y prácticas agrícolas para la adaptación y mitigación del cambio climático. Una evaluación fiable de las existencias de carbono agrícolas supone una línea de base muy útil para cuantificar su variabilidad espacial y temporal a fin de comprender mejor el ciclo del carbono y apoyar las políticas de adaptación y mitigación a escala local y regional. Por otro lado, evaluar cómo se espera que el clima afecte a los cultivos es extremadamente útil para otros actores del territorio, quienes pueden proponer y ejecutar estrategias de adaptación y mitigación a escala local i/o regional para hacer posible una agricultura más resiliente a los cambios y mejorar la seguridad alimentaria. Los objetivos específicos de esta tesis, correspondientes a los capítulos 2, 3 y 4, son: i) evaluar los stocks de carbono de la biomasa de los cultivos leñosos Mediterráneos a partir de modelos específicos para el cultivo y la zona a escala regional, ii) estimar los stocks de carbono orgánico en suelos (COS) agrícolas, evaluar la importancia de sus variables explicativas y entender la distribución espacial de los stocks de COS y iii) hacer una diagnosis de los impactos del cambio climático en las necesidades hídricas netas (NHN) y fenología de los cultivos y otros parámetros agroclimáticos a escala de cuenca y subcuenca.

Los resultados del primer trabajo (Capítulo 2) ofrecen estimaciones espaciales del total del stock de carbono en la biomasa de cultivos leñosos en Cataluña (NE de España) de unos 5.48 Tg C, presentando un valor medio de 16.44 ± 0.18 Mg C/ha. Para la década de los 2010, y a pesar de que en general el área ocupada por cultivos leñosos decreció anualmente un 2.8%, los stocks de carbono en la biomasa de cultivos leñosos aumentaron (+0.17 Tg C/año) debido al crecimiento de los cultivos leñosos de aquellas áreas que no presentaron cambios de uso de suelo. El segundo trabajo (Capítulo

3) generó una estimación espacial de los stocks de COS superficiales (0-30 cm) en los suelos agrícolas de Cataluña de unos 47.9 Tg C, presentando un valor medio de 48.8 ± 8.9 Mg C/ha. Además, mientras que la variación de stocks de COS en la parte superficial del suelo dependió principalmente del clima, la textura del suelo y variables agrícolas, los stocks de COS de la capa subterránea (30-100 cm) dependieron principalmente de los atributos del suelo. Los modelos espaciales revelaron que la relación entre los stocks de COS y sus variables explicativas variaban espacialmente. Los resultados del último trabajo (Capítulo 4) destaca el aumento generalizado de las NHN del 0.1% al 6.7% que se produciría en las tres cuencas de Cataluña estudiadas, aun siendo las dinámicas diferentes para las tres cuencas y, en general, estas tendencias variarían entre cultivos. Además, los cambios fenológicos podrían representar una gran restricción para producción agrícola. El número de días de heladas decrecerá (de -0.1 días en marzo a -8.7 días en abril) en las tres cuencas, mientras que los días extremadamente cálidos podría incrementarse (de +0.3 días en julio a +3.8 días en agosto). El ciclo de crecimiento de los cultivos podría empezar antes (de -1 días a -12 días para cultivos con temperatura base de 10ºC) y acortarse (de -8 días a -27 días). De este modo, los impactos evaluados en este trabajo, junto con el agotamiento de los recursos hídricos predicho para la zona de estudio, podrían resultar en limitaciones significantes para los cultivos si no se aplican estrategias de adaptación más allá del riego y no se enfrentan los problemas en ciclo de crecimiento de los cultivos.

En general, esta tesis aporta estimaciones espaciales de los stocks de carbono de la agricultura en Cataluña y una diagnosis de los principales impactos del cambio climático en los cultivos mayoritarios de tres cuencas representativas del nordeste Mediterráneo. Todo el conocimiento empírico obtenido en esta tesis puede contribuir significativamente a evaluar las consecuencias en términos de carbono de las prácticas y la gestión agrícola y a evaluar la adaptación de los cultivos al cambio climático a escala de paisaje para diferentes escenarios de gestión agrícola y territorial, ofreciendo asistencia a responsables políticos y actores del territorio.

Chapter 1:

General Introduction

1.1 Climate change and the Mediterranean Agriculture

Climate change (CC) is clearly and unequivocally induced by global warming. Global warming is the heating of the climate system observed since the pre-industrial period due to human activities, which have been increased greenhouse gases (GHGs) levels in Earth's atmosphere. As a matter of fact, global mean temperature has increased by about 1 ºC (0.2 ºC per decade) since the pre-industrial era. Thus, CC can be defined as a long-lasting change in the average weather defined at the local, regional, and global levels. This change in weather patterns is mainly characterized by extreme events (heat waves, droughts, freezing winters, floods, cyclones, and wildfires), changing in precipitation regime, the increase of warm temperatures, the decrease of cold temperatures or the sea level rise, among others (IPCC, 2014). Globally, the increase of temperature by the end of the present century (relative to 1986–2005) is likely to range from 0.3 °C to 4.8 °C, depending on the future Representative Concentration Pathways (RCP) established by IPCC (2014).

According to the recently published First Mediterranean Assessment Report from the network of Mediterranean Experts on Climate and Environmental Change (MedECC), "the Mediterranean Basin is at risk of suffering from levels and rates of climate and environmental changes now and in the future, exceeding global mean values" (MedECC, 2020). In future scenarios, the Mediterranean region stands out as a "hot spot" due to projections of substantial increases in temperature and decreases in rainfall (IPCC, 2014), which will lead to marked decreases in water availability throughout the Mediterranean region (Pascual et al., 2015). Notwithstanding all this, CC in the Mediterranean area also implicates other disorders, such as land use change or loss of water and air quality (MedECC, 2020). Mean temperature in the Mediterranean has increased 1.5 °C since pre-industrial times, around 0.4 °C above the global average (MedECC, 2020). Moreover, the observed decline of seasonal precipitation and the forecasted variances in magnitude and sign of these events present important challenges for the Basin (MedECC, 2020). This decrease in precipitation will enhance existing water shortages and

increase water demand for agricultural and urban uses, particularly in southern countries of the Basin, being irrigation and food security sensitive issues for the area (MedECC, 2020). Particularly, average annual precipitation in Catalonia (NE Spain) would decrease by approximately 9% and temperature would increase by +1.4 ºC until 2050 (TICCC, 2016). Furthermore, these changes will be clearly more pronounced during the summer when most crops are growing: -12.3% in precipitation and +1.6 ºC of mean temperature (TICCC, 2016). Due to CC and land use changes the Basin is currently facing important environmental issues. In fact, the extent of wildfires could rise 40-100% in comparison with the actual affected area, due to drought, land use change and high temperatures (MedECC, 2020).
In the last decades, CC has impacted on natural and anthropic systems at the global scale (IPCC, 2014). Agriculture is the anthropic system most exposed to CC (Verchot et al., 2007) since temperature and water are the main drivers of crop production (Phogat et al., 2018 Ruiz-Ramos et al., 2018). In the Mediterranean region, agriculture is expected to be heavily impacted by higher and extreme temperatures, droughts, or soil salinity. To be specific, the principal CC impacts on crops will be changes in phenology and growing cycle (Trnka et al., 2011; Caubel et al., 2015; Funes et al., 2016); higher water demands and water scarcity (Savé et al., 2012; Girard et al., 2015; Phogat et al., 2018; Saadi et al., 2015; Valverde et al., 2015; Zhao et al., 2015; Vicente-Serrano et al., 2017a, b); decreasing yields (Olesen and Bindi, 2002; Saadi et al., 2015; Zhao et al., 2015; Ruiz-Ramos et al., 2018); or soil salinity constraints (Connor et al., 2012; Phogat et al. 2018). Consequently, food production and security would be seriously compromised (Cramer et al., 2018; Mrabet et al 2020).

1.2 Mitigating climate change in Agriculture

The concept of mitigation refers to strategies implemented to reduce GHGs emissions and to increase GHGs uptakes by the Earth system and, consequently, is considered as a way to keep CC moderate rather than extreme (Denton et al., 2014).

The Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) has recognized the scientific view that the increase in global temperature should be below 2 °C (relative to pre-industrial levels) to combat CC. This temperature stabilization will require a breaking off with business as usual. Reductions in GHGs, together with adaptation, are required to maintain the increase below 2 ºC and control CC impacts (IPCC, 2014).

Mitigation in the agricultural sector can be a powerful way for countries to contribute minimizing CC impacts. Mitigation in agriculture includes: i) increasing the carbon stock and sequestration rate in biomass (above- and belowground) and soils, ii) reducing the direct emissions from agriculture (burning fossil fuels or soil respiration) and iii) avoiding the creation of new agricultural areas causing deforestation or environmental degradation (Bakkegaard et al., 2016).

Soils are the largest carbon (C) terrestrial sink at global level, containing approximately 1500 Pg C at 1 m depth (Batjes, 2014), and the C storage exceeds the C sink of plant biomass and atmosphere (Vicente-Vicente et al., 2016). However, soils can become a source of atmospheric carbon dioxide (CO_2) depending on land use or management practices (Smith, 2012). Moreover, land use change is the leading cause of soil organic carbon (SOC) depletion at the global scale, while the main current land use change is deforestation for cultivation, particularly in subtropical and tropical countries (Canadell et al., 2007). Cropland areas lose more than 50% of their original SOC at the topsoil (0-30 cm) in about 25 to 50 years after conversion from natural ecosystems due to changes in soil temperature, moisture regimes, soil disturbance and erosion (Lal et al., 2011).

Compared to their initial status before cultivation, cropland soils covering 40-50% of global land surface (Smith, 2012) have lost about 55 Pg C worldwide (Canadell et al., 2007), but at present they still store an overall pool of 157 Pg C down to 1 m depth (Jobbagy and Jackson, 2000), which is about 10% of the global SOC pool. Fortunately, agricultural soils can be managed through the implementation of Recommended Management Practices (RMPs) to improve and restore SOC content and soil properties (Lal et al., 2011). In this respect, mitigation strategies, such as the *'4 per mille Soils for Food Security and Climate'*, launched at COP21, seek to increase global soil organic carbon stock as a compensation for the global emissions of GHGs by increasing SOC at a rate of 0.4% per year in the first two meters of soil (Minasny et al., 2017).

Plants are able to capture atmospheric CO_2 but their effectiveness as a C sink depends on residence times (Quiñones et al. 2013). Forest has been widely recognized as the main terrestrial C sink of terrestrial vegetation, through sequestration of huge quantities of CO_2. However, in water-limited and degraded ecosystems such as the Mediterranean region, CC could endanger this trend. Under this scenario, Mediterranean forests have started to be affected, decreasing growth and increasing mortality, as a consequence of recent warming and extreme drought events (Vayreda et al. 2012). In this context, woody crops, particularly rainfed ones, could be considered a sustainable ecosystem based on their C sink potential for the Mediterranean area context and future CC scenarios. Compared to herbaceous crops, woody crops have a significantly larger sequestration potential sequestering C for longer periods. Therefore, managing woody crops systems could be a more feasible mitigation solution in many parts of the Mediterranean Basin than pure afforestation and reforestation projects since woody crops also provide other ecosystem and social services.

1.3 Adapting Agriculture to climate change

Adaptation is a response strategy to predict and lead with unavoidable impacts under different CC scenarios and can be defined as the adaptive capacity to respond to CC risks (Denton et al., 2014). Since agriculture is the most vulnerable anthropic activity impacted by CC, diagnosing CC risks is decisive. Assessing how CC is expected to affect crops is extremely useful for policy makers, planners, farmers and other stakeholders, who can propose and execute adaptation strategies at the local/regional scale to make agriculture more resilient to changes (Caubel et al., 2015). When seeking to identify better strategies to make agriculture more resilient, the first step is to assess the main impacts of CC on crops. The use of combined adaptation measures tailored to site-specific conditions reduces the impacts of CC more effectively than single and generalized adaptation measures. This has been shown by Ruiz-Ramos et al. (2018) and Mrabed et al., (2020) for the Mediterranean context, but can probably be applied to other regions.

CC is projected to mainly reduce surface water and groundwater resources in the Mediterranean region (IPCC, 2014; Fader et al 2020). Consequently, future water availability and demands call the current water management model into question, so adaptation decisions must necessarily be aimed at improving water management at a policy level (Iglesias and Garrote, 2015) and target both hazards and vulnerabilities, i.e., water supply and water demand issues (Ronco et al., 2017). Changing crop distribution and crop choices (Valverde et al., 2015), restricting areas of higher water-consuming crops or creating new varieties adapted to CC (Mo et al., 2017), adapting the cropping calendar (Ronco et al., 2017) and crop diversification (Lin, 2011) have all been proposed as strategies of adaptation to CC for the purpose of maintaining crop production. However, they should also be considered as part of a water management strategy. Restricting the area of high-consuming crops that free water resources at the basin level, even if they are not irrigated; changing crop distributions according to changes in phenological constraints; reducing the crop cycle and using new varieties with lower water needs would be steps in the same direction. Moreover, current changes in lifestyle (more urbanized lifestyle and more processed animal-based diet) lead southern Mediterranean countries, in particular, to be at risk of increasing their dependence on food imports and trade from abroad (MedECC, 2020). Some authors state that this tendency could be attenuated by returning to the traditional Mediterranean diet for the whole Basin population, including tourism (MedECC, 2020).

1.4 Joint Adaptation and Mitigation in Mediterranean agricultural systems

Adaptation and mitigation (ADAM) are needed working together to reduce disturbances from CC (Denton et al., 2014). Both strategies must be addressed to reduce GHGs, increase carbon stock, protect crops from extreme events, ensure sustainable use of soil and water (Prestele et al., 2018), and definitively, alleviate CC and its impacts (Denton et al., 2014). Indeed, climate-smart agriculture (CSA; FAO, 2013) has been proposed by The Food and Agriculture Organization (FAO) of the United Nations as a strategy to adapt and build resilience to CC and to reduce agricultural GHGs, while maintaining high yields and ensuring food security. Resilience defined as a system's ability to anticipate, reduce, accommodate, and recover from disruptions timely, efficiently, and fairly (IPCC, 2012), is an idea that considers how systems deal with disturbances, uncertainties and unpredictable events characterized by change and adaptation (Denton et al., 2014). Approaches such as CSA incorporate the need for adaptation and the opportunity for mitigation into sustainable agriculture without forgetting sustainability of the production process (Bakkegaard et al., 2016). The agricultural sector can combine and contribute with both ADAM activities and their synergies, as sustainable agriculture or CSA evidence. Therefore, strategies and policies must consider crop productivity and ADAM as the three interlinked pillars that support the successful achievement of targeted goals for agriculture and CC issues (FAO, 2013).

However, trade-offs between ADAM, agricultural productivity, and economic and environmental issues often arise. In some cases, adaptation may raise GHGs emissions and in other cases mitigation may obstruct adaptation. Some adaptation strategies may have negative results for mitigation, and vice versa; or mitigation strategies may have negative effects for crop production. For example, irrigation will require more energy, resulting in increased emissions if come from fossil fuels (Klein et al., 2007). Fortunately, in many cases, strategies for CC are highly interactive. Consequently, integrating ADAM can produce mutual advantages in most cases (Denton et al., 2014). More synergies can be found in strategies based on the improvement of soil through adding organic matter. Increasing organic matter at soil will not only improve the fertility, the nutrient status and water holding capacity of the soil, but it can also alleviate soil erosion and sequester carbon (Blanco et al., 2009). Strategies focus on ensuring food production and with high adaptation and mitigation potential include restoring degraded land, introducing agroforestry and tree-based agriculture at the landscape level and mulching or the use of organic manure at the field level (Bakkegaard et al., 2016).

Unfortunately, ADAM strategies are often faced individually in agriculture due to the negative interactions between them (Smith and Olesen, 2010). For example, afforestation and reforestation increase carbon stocks and the uptake of CO_2 from the atmosphere, but these can also reduce water availability, causing competition between land uses downstream such as urban or agricultural uses in semiarid and arid regions (Huettner, 2012; Kongsager et al., 2013). Some regions, such as the Mediterranean, have limited capacities to mitigate or adapt to CC at all scales. That is why, ADAM strategies are fundamental for effective implementation of climate impacts management and alleviation (Bakkegaard et al., 2016). Mediterranean woody crops and agroforestry may have the opportunity to supply food security and landscape diversification to increase adaptive capacity when climate impacts, while mitigating through carbon sequestration on woody biomass. Adaptation strategies based on crop diversification can expand economic possibilities and generate mitigation benefits, such as carbon sequestration (Bakkegaard et al., 2016). Nevertheless, working on land use management at different scales is crucial for creating ADAM synergies with low cost (Bakkegaard et al., 2016). The approach focused on joining ADAM at the landscape level should base on: i) landscape diversification (diversity of crops, agroforestry, natural and restored areas), ii) the introduction of silvopastoral systems, livestock diversification and management, and iii) land management (Harvey et al., 2014). Moreover, joining ADAM at the landscape level, from the field, local or regional levels, enables to create a mosaic of ecosystems.

Ecosystem services (ES) are direct or indirect benefits from ecosystems to humankind and social welfare. ADAM interactions will smooth the impacts of CC and generate ecosystem services, such as biodiversity and carbon stocks. Payment for Ecosystem Services (PES) aims to improve the environment cost-effectively for the supply of ecosystem services from ADAM actions on agriculture, such as water regulation, soil improvement and CO_2 uptake (Bakkegaard et al., 2016). PES concept and payment schemes such as REDD+ (Reducing emissions from deforestation and forest degradation from UNFCCC) show increasing potential when incorporating adaptation activities as well. However, C stocks from Mediterranean agriculture, particularly from tree-based crops and orchards, are excluded from mitigation policies such us REDD+ (FAO, 2018) despite their important role in the global C cycle and their widespread distribution in the Basin. “Trees outside forests” are frequently ignored as C pool and little information is available on C stocks and C sequestration potential in these systems (De Foresta et al., 2013). Compared to other systems, woody crops can mitigate CC because of their wide spatial distribution and their significant capacity of C sink, as mentioned above. For the Mediterranean Basin, managing woody crops systems could be a more feasible mitigation and adaptation strategy in water-limited regions of the Mediterranean Basin compared to reforestation (as promote strategies like the European Green Deal) since these could derive in degraded ecosystems due to CC, water resources depletion and disturbances such as wildfires (Sachs et al., 2019). However, woody crops also provide food, work, economic profit, population maintenance and they represent strong links with the Mediterranean landscape, history and culture.

In fact, there is a lack of coordinated funding for ADAM. There are a lot of issues to consider in order to improve payments for carbon sequestration and to incentive adaptation actions. It requires conceiving management strategies at the landscape level and ensuring the decision-making.

Empirical evidence of ADAM issues is still limited because of the lack lack of studies and experiences until now (Denton et al., 2014). So, empirical knowledge on ADAM at the landscape level is necessary to implement effective experiences. More research of the ADAM synergies is needed to explore the linkages between agriculture, forest and other land uses at different levels: landscape, country and international (Bakkegaard et al., 2016). At the landscape scale it is crucial to monitor agriculture and CC impacts in order to test different scenarios (Sachs et al., 2010) that help policy- and decision-makers to picture possibilities of joining ADAM with food security, ecosystem services and other related objectives.

Moreover, significant challenges are posed to join ADAM strategies: i) the scale (local for adaptation; global for mitigation), ii) time horizon for implementation (short-term for adaptation; long-term for mitigation), iii) the funding availability mentioned above, and iv) the metrics to measure, since no metrics exits for adaptation or for evaluating synergies (Bakkegaard et al., 2016).

The main objective of this thesis is assessing the role of the Mediterranean agriculture as a carbon sink through the quantification of carbon stocks in above- and belowground biomass and soils of agriculture in Catalonia (NE Spain) and, also, reaching a diagnosis of the CC impacts and vulnerabilities that the Mediterranean agriculture faces so as to generate a baseline of empirical knowledge necessary to explore and test ADAM scenarios that can help in the decision-making.

1.5 Objectives.

The specific objectives of the thesis, corresponding to each of the following four chapters, are detailed below:

1. Chapter 2 represents the first study to assess woody crops systems as a C sink in a significant Mediterranean area, NE Spain. The first aim of the study is to assess Mediterranean woody crops biomass as a carbon sink which is based on literature data, destructive and non-destructive measurements conducted for each woody crop established in this study to analyze C sink as a function of woody crop age. The second goal was to estimate the total carbon sequestration from woody crops in NE Spain by scaling up at the municipality level. Finally, the last goal was to assess carbon stock changes during the period 2013-2019 derived from land use changes in the study area.

2. Chapter 3 provides the first assessment of agricultural soil organic carbon (SOC) stocks in topsoil (first 30 cm) and subsoil (30 cm to 100 cm) while considering the main SOC drivers for Catalonia. In this chapter, geostatistical techniques were applied to model SOC stocks for agricultural soils in the study area based on legacy data from 7,245 agricultural soil profiles. The main objectives of the chapter were: i) to assess SOC stocks at two depth intervals (top and subsoil); ii) to identify the main explanatory variables driving SOC stocks at the regional scale; iii) to analyse the spatial variability of relationships between SOC stocks and drivers; and iv) to map SOC stocks at the regional scale using a subset of explanatory variables (climatic, topographic and agricultural management).

3. For chapter 4, three basins were chosen to represent the diversity of the Mediterranean at a local scale. They feature a wide range of topographic, climatic and environmental conditions, and land uses of the Mediterranean region, including inland vs. coastal differences, which makes this study novel. This study applied an improved upscaling of net hydric needs (NHN) at basin scale for the first time. The improved upscaling uses homogeneous climate, crop type and soil type units. This leads to an understanding of

how changes in basin water balance result from the combination of changes in crop phenology, potential evapotranspiration and crop distribution in each basin. The main goals of this chapter were: (i) to estimate annual net hydric needs (NHN) of major crops in the three basins for the baseline period and two future periods under CC conditions, in order to assess agricultural suitability; (ii) to estimate the monthly pattern of NHN of some crops, which can help to explain the different annual NHN responses of crops to CC; (iii) to estimate a set of agroclimatic parameters capable of indicating the consequences of CC for crop phenology and growing cycle, in order to better understand and manage the risks posed by CC; and (iv) to identify a set of possible adaptation solutions, in view of the results obtained.

4. The final objective of this thesis was to discuss in Chapter 5 how the results obtained could become a baseline of empirical knowledge to test different scenarios that can help to design ADAM strategies in the decision-making process to. An example of testing mitigation scenarios about animal manure management at the local level in Catalonia was provided.

1.6 Study Area

The study area is the agricultural land of Catalonia in the north-eastern Iberian Peninsula (Fig. 1). Catalonia presents Mediterranean climatic conditions characterized by mild winters and hot and dry summers (Terradas and Savé, 1992), but diverse meso- and micro-climates can be found. A strong climatic gradient (Martin-Vide et al., 2016) is defined (Fig. 1) by mean annual temperature (ranging from 0 to 17.3 °C) and annual precipitation (from 1,464 mm in the Pyrenees to 335 mm in the Ebro Valley). Moreover, a marked continentality

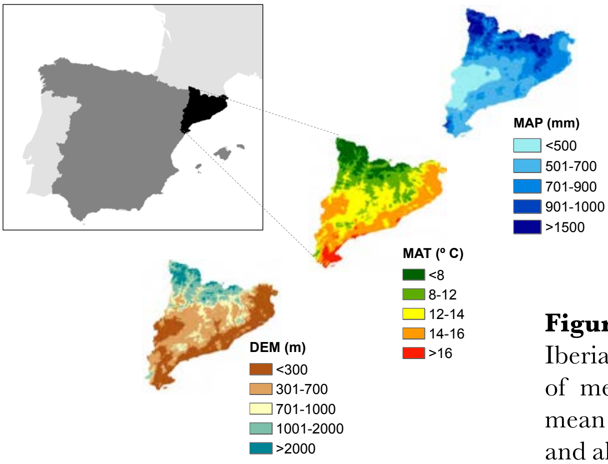

Figure 1. Location of Catalonia in the Iberian Peninsula and spatial distribution of mean annual temperature in ºC (MAT), mean annual precipitation in mm (MAP) and altitude in meters by the digital elevation model (DEM) in the study area.

According to SIGPAC (2019), the Agricultural Plots Geographical Information System for the year 2019, the cropland area in Catalonia is about 8,733 km^2 (27% of Catalonia; Fig. 2), not including pastures. Pastures (including wooded and shrubby pastures) and forests occupy 63% of the total area in Catalonia, respectively. Urban areas and other uses (unproductive, water bodies and roads) comprise 10% of the zone. Almost 66% of the cropland area remains under rainfed conditions. Arable land is the most widespread cropland, representing 63% of cropland area. Woody crops contribute 37% (3,246 km^2) of the total agriculture land-uses and are mostly located in the southern half of the region (Fig. 2). The major woody crops are vines, olive, non-citrus fruit trees and citrus. Vines represent 18% of the woody crops area, olive 37%, fruit trees 25%, nuts 17% and citrus fruit 3%. The most important rainfed woody crops are vines, olives and nut-fruit trees and their geographical distribution is related to low annual precipitation. Irrigated fruit trees orchards are mainly located in the central valley, where of annual precipitation is one of the lowest. The Catalan agriculture, and most particularly woody crops such as rainfed vines, olive or nuts trees, have strong territorial, historical and cultural links with Mediterranean areas.

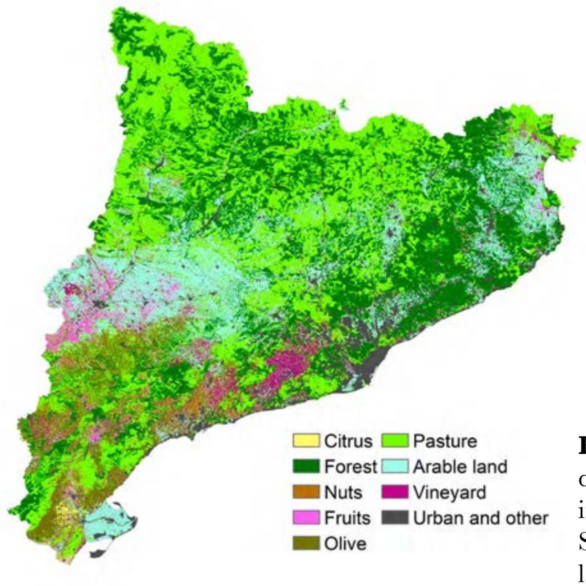

Figure 2. Spatial distribution of land uses in Catalonia according to SIGPAC (2019). Pasture land use includes woody and shrubby pastures.

Agriculture in the study area is mainly developed over Inceptisols and Entisols (mainly Fluvents and Orthents) and, to a much lesser extent, over Alfisols, Aridisols and Mollisols (SSS, 2014). Aridisols (mainly located in the Ebro valley, a historically irrigated cropland area) are typical of areas where evapotranspiration is higher than precipitation, limiting crop production except when irrigation is applied, in which case high yields are obtained. Agricultural soils are mostly medium (loamy) textured, with a basic reaction. Calcium carbonate-rich soils are dominant, often with a petrocalcic horizon as a root-limiting layer.

All these traits made the study area quite representative of the Mediterranean agriculture.

1.7 Background

In Spain, and particularly in Catalonia, there has been an important concern to mitigate climate change by adapting activities and sectors in order to create a resilient region.

The ACCUA project in the early 2010s (ACCUA, 2011; Savé et al., 2012; Lopez-Bustins et al., 2013, Pascual et al., 2015) noted that Catalonia will have to adapt to an increasingly arid future, and it also warned about the necessity of implementing strategies and policies to adapt to climate change.

Also, since the Second (SICCC, 2010) and the Third (TICCC, 2016) Report of the Canvi Climatic in Catalonia, an important scientific work has been done to assess carbon sinks of different ecosystems, giving forests a predominant role, for their extent and functionality, followed by agricultural habitats.

All this knowledge, supported by the important CONSOLIDER MONTES project (MITECO, Spanish Government) has allowed a formal link with the 4x1000 strategy proposed at COP (Conference of the Parties to the United Nations Framework Convention of Climate Change) 21 and 22 and other actions such as the Global Research Alliance or the MedECC (Mediterranean Experts on Climate and environmental Change) network with its First Mediterranean Assessment Report (MAR1, MedECC, 2020).

Therefore, Catalonia is the geographical area where this thesis is focused on, a region with a traditional scientific and technical work serving as an important background for this thesis.

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Chapter 2

Carbon stocks and change in Mediterranean woody crop biomass over the 2010s in NE Spain.

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Abstract

This paper estimates above and belowground biomass carbon stock of woody crops in the NE Iberian Peninsula in 2013 and changes in this stock over the period to 2019. For this purpose, eight crop- and site-specific equations relating biomass or biometric variables to crop age were calculated from measured, estimated, donated and literature data. Census of Agriculture data were used to scale results from individual data up to the municipality level at the regional scale. Results show that in woody cropland in NE Spain the total biomass carbon stock in 2013 was 5.48 Tg C, with an average value of 16.44 ± 0.18 Mg C/ha. Between 2013 and 2019, although in general the area covered by woody crops showed an annual decrease of 2.8%, carbon stocks in biomass of these crops recorded an annual increase of 3.8% (+0.173 Tg C/year) due to the growth of the remaining woody cropland. This estimation of carbon stocks may contribute to the assessment and management of carbon storage as an ecosystem service provided by Mediterranean woody cropland for mitigating climate change, particularly in this climate change hot spot, and in combination with adaptive strategies this storage could support a productive and resilient agro-food system.

Highlights

- Eight biomass equations to estimate the biomass of six Mediterranean woody crops were performed.
- Upscaling of biomass carbon stocks in NE Spain and changes in these over the course of 6 years were assessed.
- The estimated biomass carbon stock was 5.48 Tg C with an average of 16.44 ± 0.18 Mg C/ha.
- Carbon stocks increased 19% between 2013 and 2019 despite woody cropland regression.
- Results may help to evaluate the carbon consequences of cropland management.

Keywords

Mitigation; woody cropland; agriculture; climate change; allometries; biomass equations; upscaling

1. Introduction

Climate change (CC) is clearly induced by the global increase in greenhouse gases (GHGs) emissions, mainly carbon (C) compounds such as carbon dioxide (CO_2) or methane (IPCC, 2014). Vegetation can capture CO_2 through photosynthesis and store it by transforming it into biomass (IPCC, 2014).

In this respect, carbon sequestration and storage in biomass and soils has become one of the most important mitigation measures in the fight against CC. Therefore, reliable evaluation of C fixation in terrestrial sinks would be useful, in order to quantify their spatial and temporal variability, gain a better understanding of the carbon cycle and assist mitigation policies worldwide (Quiñones et al., 2013; Huffman et al., 2015). Thus, plants are able to capture atmospheric CO_2, but their effectiveness as a C sink depends on residence times (Quiñones et al., 2013).

Forest has been widely recognized as the main C sink of terrestrial vegetation through sequestration of huge quantities of CO_2. However, in ecosystems that are water-limited and degraded due to CC, such as those in the Mediterranean, water availability and disturbances could curb the increasing trend of forest as a carbon sink (Vayreda et al., 2012b). On the other hand, woody crops, particularly rainfed crops, could be considered a sustainable ecosystem based on their moderate C sink potential (when compared with forest) in the context of the Mediterranean area and future CC scenarios, besides their great importance as a food source (MedECC, 2020). Compared to herbaceous crops, woody crops have a significantly larger sequestration potential and can sequester C for longer periods. Many annual crops can fix large quantities of C, but their biomass usually decomposes rapidly and the rate and return of uptake are very fast (Liguori et al., 2009). Since biomass accumulated by these cover types in a single year is assumed to be equal to biomass losses from harvest and mortality for the same year, there is no net accumulation of carbon stock (Huffman et al., 2015). This knowledge is important, as managing woody crop systems could be a more feasible mitigation solution than pure afforestation or reforestation in many parts of the

Mediterranean basin, given that woody crops also provide food, work, economic profit and population maintenance, and they are closely linked with the landscape, history and culture of the Mediterranean.

Allometric equations are crucial for understanding carbon stocks in forests and other terrestrial vegetation (Alvarez et al., 2012). These equations are the most widely used methodology in biomass estimation based on data from destructive (harvest) and non-destructive (biometric measures) methods (Vashum and Jayakumar, 2012). Several allometric equations for forest above- (ABGB) and belowground biomass (BGB) have been published since the beginning of the 21st century (Valentini et al., 2000; Chave et al., 2005; Montero et al., 2005; Djomo et al., 2011; Ruiz-Peinado et al., 2011; Alvarez et al., 2012; Herrero and Bravo, 2012; Ruiz-Peinado et al., 2012; Vayreda et al., 2012a; Thurner et al., 2014; Gonzalez et al., 2015; Ruiz-Peinado et al., 2017).

To date, there have been fewer studies on the ability of woody crop biomass to act as a C sink compared with corresponding research on forests, and the contribution of croplands to global and national C balances is not fully understood. At present, there are only a few studies that assess biomass and carbon sequestration in woody crops focused on Mediterranean regions, and most of these have been made during the last decade. Two key studies on citrus have been conducted in Mediterranean regions such as Eastern Spain (Iglesias et al., 2013; Quiñones et al., 2013). With respect to vines, some studies have been published about carbon stocks in California (Keightley, 2011; Williams et al., 2011; Iglesias et al., 2013) and allometries in Spain (Miranda et al., 2017). A number of studies have estimated woody biomass on agricultural land in non-Mediterranean regions (Kumar et al., 2010; Kuyah et al., 2012a, b; Kongsager et al., 2013; Kuyah et al., 2016; Ortiz-Ceballos et al., 2020; Asigbaase et al., 2021) and globally (Zomer et al., 2016; Spawn et al., 2020). There are fewer studies on changes in land use (LUC) and associated carbon sequestration potential (Padilla et al., 2010; Huffman et al., 2015). In general, despite growing interest in developing agro-environmental policies associated with CC mitigation, studies of crop species of agricultural importance are scarce (Iglesias et al., 2013).
Understanding woody crops as a C sink in the Mediterranean area

would link CC mitigation and adaptation, and an enhancement of this link has been called for by several authors (Kongsager et al., 2013; MedECC, 2020). In this context, there is a need to complete a first level assessment of woody crop biomass as a C sink for the Mediterranean area. Moreover, specific models should be developed for sites, crops and typical culture practices carried out in order to move up through the Tier Methods established by the IPCC (IPCC, 2006), gain in accuracy, and reduce uncertainties in future assessments (Huffman et al., 2015). Research into allometric equations applicable to woody crops is important for accurate accounting of C stocks worldwide that could assist mitigation policies (Kuyah et al., 2012a), such as REDD+ (reducing emissions from deforestation, forest degradation and enhancement of forest C stocks), together with country policies and some compensatory policies and strategies developed from COP21 and 22 (United Nations Climate Change Conference). As such, woody crop systems may also be an important element in increasing adaptive capacity to CC and other pressures currently faced by the Mediterranean area.

The primary aim of this study is to assess Mediterranean woody crops as a carbon sink with reference to literature data and destructive and non-destructive methods conducted for each woody crop as a function of crop age. The second aim is to estimate the total woody crop carbon stock in NE Spain by scaling up at the municipality level. The third and final aim is to assess carbon stock changes due to land use change in the study area over the period 2013-2019.

2. Material and methods

2.1. Study Area

The study area consists of woody cropland in Catalonia (NE Iberian Peninsula). This region presents Mediterranean climatic conditions characterized by mild winters and hot and dry summers, with mean temperature ranging from 0 to 17.3 °C and annual precipitation from 1,464 mm in the Pyrenees to 335 mm in the central valley (Fig. 1).

According to SIGPAC (2013), 26% of the land in Catalonia (847,977 ha) is used for agricultural purposes and, more specifically, woody cropland accounts for 10.4% of the total land area (335,029 ha). Woody crops represent 40% of total agricultural land use, with most of these to be found in the south-western half of the region (Fig. 1). The principal woody crops are vines, olive, non-citrus fruit trees and citrus. Vines represent 17% of the total area devoted to woody crops, olive 37%, fruit trees 26%, nuts 17% and citrus fruits 3%. The most important rainfed woody crops are vines, olive and nut trees, and their geographical distribution corresponds to areas with low annual precipitation and extreme temperatures. However, fruit tree orchards, considered as high-water consuming crops, are mainly located in the central valley, where annual precipitation is lowest (Funes et al., 2021). Woody crops in general and particularly rainfed woody crops such as vines, olive and nut trees have strong territorial, historical and cultural links with Mediterranean areas. In this respect, NE Spain is highly representative of the Mediterranean crop pattern. This study conducted a cropland classification of major Mediterranean woody crops in NE Spain, focusing on 5 classes: vines, olive, citrus, fruit orchards and nuts.

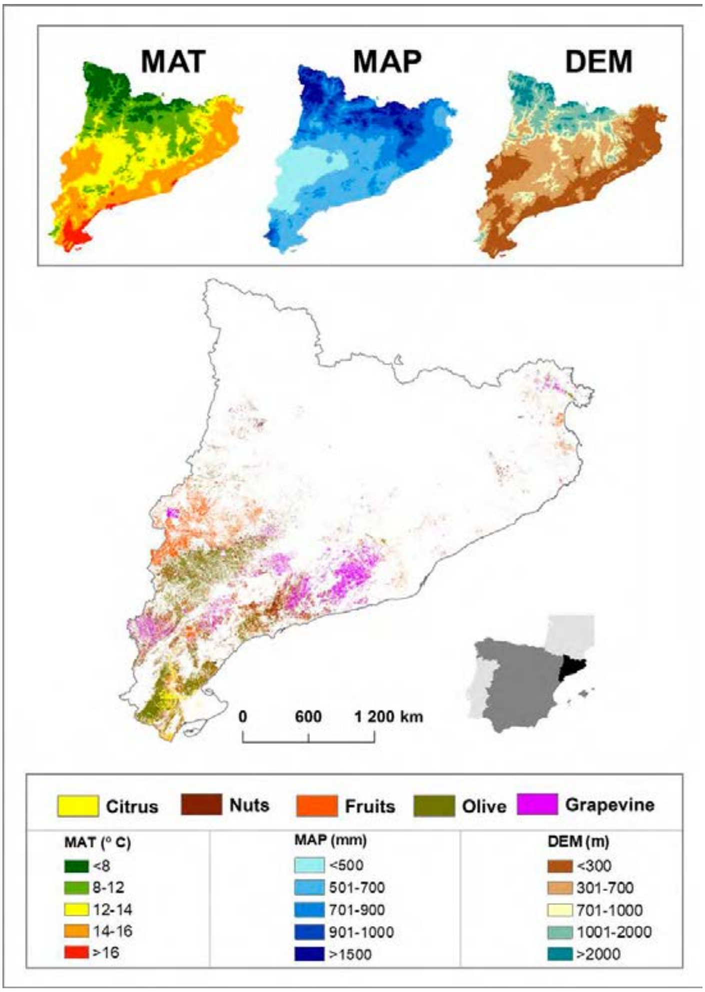

Figure 1. Study area: location, climatological information (MAP, mean annual precipitation, and MAT, mean annual temperature), topographical information (DEM, digital elevation model) and woody crop distribution

2.2. Carbon stocks estimation in woody crops

2.2.1 Estimation of above and belowground biomass

Aboveground biomass equations (or other biometric variables, depending on the case) were fitted for citrus, seed and stone fruits, nut trees, olive and vine cropland classes as a function of age from two data sources: literature and own or donated data, based on destructive or non-destructive methods. To estimate aboveground biomass (dry matter/plant) as a function of crop age and to build equations for each type of woody crop in order to perform biomass estimations, biomass or other biomass-related biometric variables were collected and paired with age data in different conditions (type of soil, agronomic practices, training, cultivars, planting density, irrigated/rainfed, etc.) from literature or from own measurements and from field data donated by other authors. Biomass estimations for olive and nut trees had to be determined indirectly. First, data from biometric parameters (trunk diameter or trunk basal area) were measured and collected from literature or donated by authors. Next, regression models were fitted to these datasets. Finally, conversion equations from literature were used to derive estimations of biomass.

Belowground biomass was mainly calculated for each type of woody crop by using Root:Shoot ratios from literature, or in other cases it was estimated as a function of age by fitting specific equations for belowground biomass. Data obtained from literature were only selected from studies performed under field conditions, excluding laboratory and experimental greenhouse studies. Agronomic practices considered very different from typical practices in Spain and which have a direct impact on tree or vine architecture were also excluded. The bibliographic search was restricted to areas with Mediterranean conditions (Fig. A.1 and A.2. in Appendix A).

Grapevine

The grapevine dataset comprises data from literature (Saayman and Huysteen, 1980; Williams and Biscay, 1991; Clingeleffer and Krake, 1992; Mullins et al., 1992; Araujo et al., 1995; Williams, 1996; Santesteban and Royo, 2006; Keightley, 2011; Santesteban et al., 2011a, b; Williams et al., 2011; Escalona et al., 2012; Goward, 2012; Santesteban et al., 2013), and data from destructive and non-destructive methods. Some of these (from Barcelona, Spain) included destructive methods to measure belowground biomass. Detailed information relating to the vine dataset including sources, references, location, dataset size and some agronomic culture traits can be found in supplementary information (Table B.1. in Appendix B). Details about the non-destructive and destructive measurement procedure can be found in Appendix C.

Fruit trees: seed and stone fruit

Olive

Olive biomass data from destructive measures is difficult to find in literature, because these measures are labor-intensive, expensive and time-consuming. Due to the difficulties encountered when researching olive biomass data in a reasonable (appropriate) age range, the calculations were made by establishing a relationship between trunk basal area and crop age. Trunk basal area (TBA; cm2) is a standard biometric variable and could be directly related with tree biomass, as is widely known in forest allometric relationships. Trunk basal area data or other directly related biometric variables such as trunk basal diameter at 30 cm from the ground (TD, cm) were collected from literature (Aragues et al., 2005; Almagro et al., 2010; Aragues et al., 2010; Bustan et al., 2011; Fernández et al., 2011a; Fernández et al., 2011b; Segal et al., 2011; Arnan et al., 2012; Gucci et al., 2012; Larbi et al., 2012; Mezghani et al., 2012; Nardino et al., 2013), measured or donated by other authors. More details about data, measurements and data homogenization can be found in Appendix C and in Table B.2 of Appendix B. To estimate ABGB from TBA, the equation drawn from the experiment performed in 18 young olive orchards published in Villalobos et al. (2006) was used. According to the literature reviewed (Appendix C) and following Nardino et al. (2013), it was assumed that olive root biomass of both young and old trees was 30% of the total accumulated by their aerial part.

The fruit trees dataset comprises data from literature (Grossman and DeJong, 1994; Caruso et al., 1999a; Caruso et al., 2001; Inglese et al., 2002; Sofo et al., 2005; Solari et al., 2006; Bravo et al., 2012; El-Jendoubi et al., 2013) and from destructive and non-destructive methods. The data only consider permanent structures excluding pruning material, leaves and fruits. Two different equations were built from the dataset: seed fruit trees and stone fruit trees. The seed fruit trees equation was fitted with data from apple and pear trees, whereas the stone fruit trees equation was built with data from peach and nectarine trees. Detailed information relating to dataset sources, references, location, dataset size and some agronomic culture traits for seed and stone fruit trees can be found in Table B.3 in Appendix B. Information about non-destructive and destructive methods appears in Appendix C. The Root:Shoot ratio for fruit trees was considered to be 0.30. This value is based on dry weight data published for apple trees (Panzacchi et al., 2012) and peach trees (Xiloyannis et al., 2007).

Nut trees

As with olive biomass, in the case of nuts the calculations were performed on the basis of a relationship between TD at 30-40 cm from the ground and crop age. TD came from measurements of almond trees that were taken in different trials at IRTA facilities located in Lleida and Tarragona. Due to the difficulty in obtaining a specific allometry of trunk diameter-aboveground biomass for nuts, a general equation for forest tree species was used, namely the group “other Broadleaves” from Montero et al. (2005), based on the similar tree morphology between nut trees and forest species such as the chestnut, carob or European nettle tree. Detailed information relating to dataset sources, references, location, dataset size and some agronomic culture traits for nut trees can be found in Table B.4 in Appendix B.

Citrus

The citrus biomass dataset only comprises data from literature, from two references in particular. Quiñones et al. (2013) showed aboveground and belowground biomass data from 2 to 14-year-old Navelina orange trees (Citrus sinensis L.) in Valencia (Eastern Spain), while Iglesias et al. (2013) showed aboveground and belowground biomass data from 2 to 14-year-old Clemenules trees (Citrus clementina Hort. ex Tan.) in Valencia (Eastern Spain). In contrast to the other woody crops studied, citrus fruit trees are evergreen, so leaves are taken into consideration in the aboveground biomass, excluding annual pruning.

2.2.2 From biomass to carbon stock

The C content of biomass dry matter used in the estimations were different for each woody crop class. Based on the literature reviewed (Appendix C) values of C content in biomass and averaged them by woody crop class, we assumed an average C content in biomass of 48.4% for olive, 44% for vines, 46.9% for fruit trees and nut trees and 44.8% for citrus was assumed. Propagation of uncertainty in C content values were also determined with bootstrap techniques (see section 2.2.4 below).

2.2.3 Upscaling carbon stocks: from the tree to the regional level

The total carbon stock from woody crops was integrated, scaling up from the tree to the regional scale (Catalonia, NE Spain) by using the official information available about the spatial distribution of crop culture traits (age, plant density, etc.). The upscaling was based on official or statistical information about plant density at the municipality level or age distribution around the territory in each type of woody crop (Table B.5 of Appendix B). The availability of this official information at this level was a limiting factor for some of the woody crop classes studied (see Appendix C for more details about the data from official registries used in the upscaling procedure). The most updated official information available corresponded to the year 2013, which explains why the upscaling of carbon stocks was specifically built for the year 2013.

In the case of crop areas older than the oldest established in allometries, the same carbon stock was assigned. In other words, if it was necessary to estimate carbon stocks in a 20-year-old citrus orchard in Catalonia, carbon stocks corresponding to a 16-year-old orchard were assumed, the oldest age in the biomass-age function for citrus used in this study.

C stock per individual (kg C/individual) depending on age was multiplied by the plant density to estimate the carbon density (Mg C/ha). The total C stored was calculated at the municipality level multiplying by the area (ha) of each woody crop at a particular age and the plant density obtained from official registries. The distribution area for the different woody crop classes is based on SIGPAC (2013). The description and information about SIGPAC can be found in Appendix C in the details about scaling up performance.

To estimate average annual carbon sequestration values (Mg C/ha/year) for each woody crop during its mean life, an estimation was made of the mean value of carbon stock differences between consecutive ages per individual. Finally, the mean value was multiplied by the representative plant density for each crop in the study area.

2.2.4 Uncertainties in carbon stock estimations

Propagation of uncertainties in C stock estimation was computed with bootstrap methods (see e.g. Davison and Hinkley, 1997). Samples were drawn randomly with replacement to calculate a bootstrap estimation of a) the expected biomass, for citrus trees, seed fruit trees, stone fruit trees and vine; b) TD, for nut trees; or c) TBA for olive trees. Then, for a) the biomass-C stock conversion was carried out by multiplying those biomass values with samples of C content drawn randomly with replacement. For b) and c), a further step was required. TD-biomass conversion in b) was achieved by directly applying the Montero et al. (2005) equations. TBA-biomass conversion in c), on the other hand, was accomplished by bootstrapping the datasets in Villalobos et al. (2006), regressing (to obtain a bootstrapped estimation of the TBA-biomass relationship) and applying the results of the regression to the bootstrapped TBA estimation. Finally, confidence intervals (CI) at the 95% level were determined as

$$CI = \left(C_{\mathrm{T}} + z_{\frac{\alpha}{2}} \cdot \sigma_{\mathrm{T}}, C_{\mathrm{T}} + z_{1-\alpha/2} \cdot \sigma_{\mathrm{T}}\right) \qquad \textbf{Eq. 1}$$

where C_T is expected total C stock for a given crop and area, σ_T stands for the bootstrapped standard deviation and $z_{\alpha/2}$ and $z_{1\text{-}\alpha/2}$ are the corresponding quantiles of the normal distribution (for $\alpha=0.05$, $z_{\alpha/2}$ and $z_{1\text{-}\alpha/2}$ are approximately -1.96 and +1.96, respectively).

2.3 Carbon stock changes in woody crops (2013-2019)

2.3.1 Land use changes

First, land use changes in Catalonia from 2013 to 2019 were assessed using SIGPAC. All the SIGPAC features for 2013 and 2019 were converted to raster (100 m pixel size), land uses were reclassified to 10 classes and a land use transition matrix was calculated.

2.3.2 Carbon stock changes

Carbon stocks for woody crops in 2019 were calculated using the same procedure for woody crops in 2013 described above in section 2.2.3. For the year 2019, the woody crops area from SIGPAC (2019) was used, making two assumptions: i) crops grew for 6 years in the remaining areas and ii) the new crop areas were 3 years old (half the time between the two maps). The upscaling was performed considering the same spatial distribution for ages (but adding 6 years) and plant density from 2013, as no updated information was available.

3. Results

3.1 Building biomass or biometric equations for biomass and carbon density estimation

Depending on data availability, eight equations for direct prediction of biomass (ABGB and BGB) or indirect prediction through biometric parameters (TBA or TD) are provided. Figure 2 presents all the fitted curves as a function of crop age for woody crops performed in the study. Details of the resulting equations are shown in Table B.6 (Appendix B).

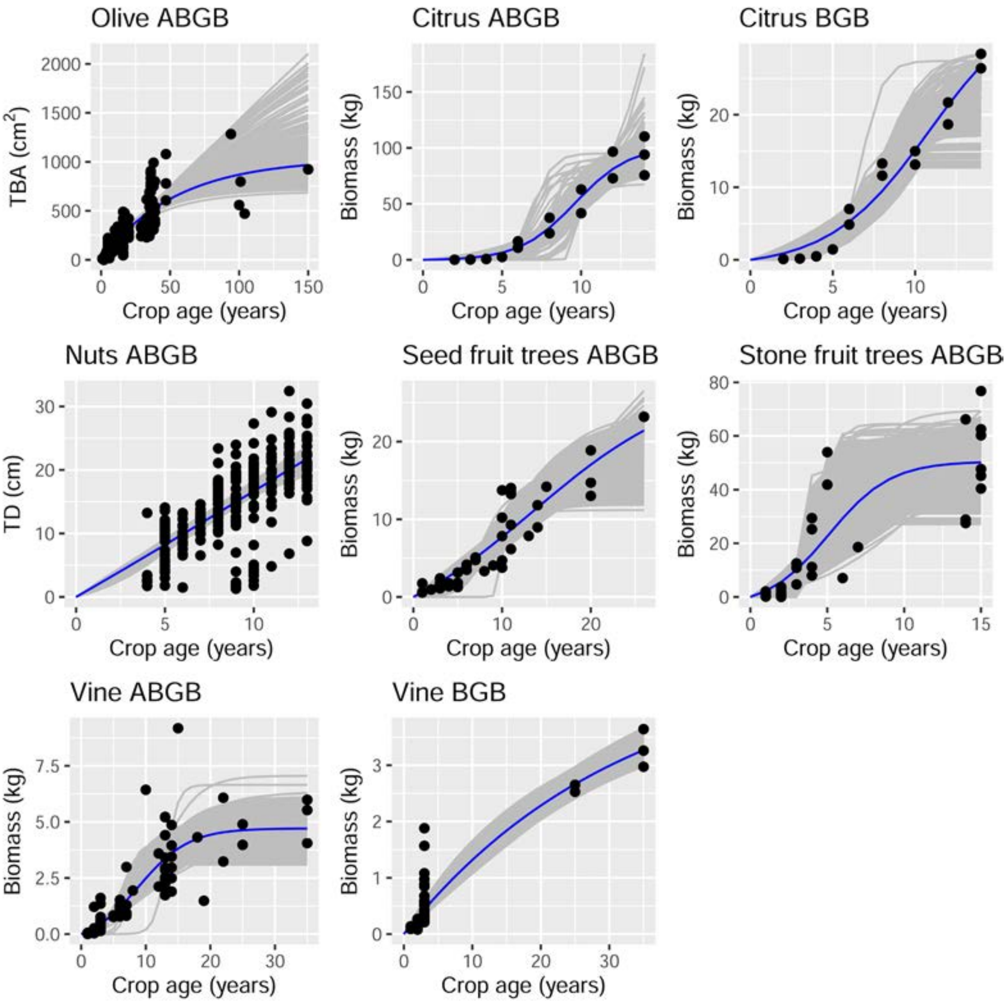

Figure 2. Fitted curves of biomass or biometrics variables (TBA and TD) as a function of age (blue lines) to estimate biomass of permanent woody crop structures per individual (tree or vine). Grey lines correspond to 1000 bootstrap simulations and black dots indicate actual observations.

Based on these equations, C stock values per crop type at individual level were computed, either directly (i.e., age→biomass→C→stock) or indirectly (i.e., age → TBA → biomass → C stock for olive, or age→TD →biomass→C stock for nut trees).

The estimated carbon stock at the individual level (kg C/tree or vine) varies depending on the age and the type of equation proposed

(Fig. A.3 in Appendix A). The lowest individual values are found in vineyards where, for example, mature vines between 10 and 20 years of age showed ABGB carbon stocks ranging from 1.09 to 1.95 kg C/vine and BGB carbon stocks from 0.58 to 1.01 kg C/vine. Highest individual carbon stocks were estimated for olive ABGB ranging from 27.2 to 97.3 kg C/tree, for example, in the case of crop ages from 10 to 50 years.

Annual carbon sequestration in woody crops can be found in Appendix B (Table B.7) for different crop age ranges. The average sequestration rate for vineyards was around 0.35 Mg C/ha/year for 0 to 35 years considering a representative plant density of 3,500 vines/ha. Olive groves displayed similar values with 0.38 Mg C/ha/year (average value for 0 to 50 years with 150 trees/ha). Fruit trees yielded an average annual sequestration rate of 1.68 and 1.84 Mg C/ha/year for seed fruit and stone fruit, respectively, in a plantation with stand ages ranging from 0 to 26 and 0 to 25 years and plant density of 3,300 and 1,500 trees/ha, respectively. Finally, nuts and citrus presented an average annual carbon sequestration rate of 2.25 and 3.32 Mg C/ha/year, from 0 to 13 and 0 to 14 years, and with 200 and 800 trees/ha, respectively.

3.2 Carbon stock upscaling to the regional level

Average carbon density (above and belowground) in permanent structures of woody crops in Catalonia for the year 2013 was 16.44 ± 0.18 Mg C/ha (mean ± 95% confidence interval computed from the bootstrapped standard deviation). Average carbon densities for each woody crop type in Catalonia ranged from 6.40 ± 0.02 Mg C/ha in vineyards to 27.40 ± 0.34 Mg C/ha for nuts (Table 1). The total carbon stock in biomass of woody crops in Catalonia for 2013 was 5.48 Tg C (Table 1), mainly from olive (39.1%), nuts (27.9%) and fruit orchards (22.0%).

Table 1. Woody crop area (ha), average carbon density (Mg C/ha), uncertainty of estimations (upper and lower limits of 95% confidence interval) and total carbon stock (Tg C) of biomass in woody cropland in Catalonia. The proportion of each crop type to the total woody crop area (ha) and to total carbon stock (Tg C) is shown in brackets (%).

		Average carbon density			**Total carbon stock**
		MgC/ha			**TgC**
Crops	**Area (ha)**	**Mean Value**	**Lower limit**	**Upper Limit**	
Citrus	9,346 (2.8%)	25.95	25.77	26.13	0.24 (4.4%)
Nuts	55,893 (16.8%)	27.40	27.06	27.75	1.53 (27.9%)
Fruits	87,134 (26.1%)	13.86	13.70	14.01	1.21 (22.0%)
Olive	125,441 (37.6%)	17.09	16.87	17.31	2.14 (39.1%)
Grapevine	55,612 (16.7%)	6.40	6.38	6.42	0.36 (6.5%)
Total Woody Crops	**333,426**	**16.44**	**16.26**	**16.62**	**5.48**

Spatial distribution of carbon density at the municipality level in 2013 is shown in Figure 3 (A) and ranges from 0.10 to 67.13 Mg C/ha. Values of less than 1 Mg C/ha are distributed across several municipalities in the Pyrenees and pre-Pyrenees, corresponding to fruit orchards. Values ranging from 1 to 10 Mg C/ha are mainly concentrated in the central pre-coastal area, corresponding to vineyards. The highest carbon densities (> 30 Mg C/ha) are concentrated in NE Pyrenees and NE and central pre-Pyrenees, represented by fruit trees, nuts and olive orchards, and in SE Catalonia by nuts and olive groves. The spatial distribution of uncertainties is shown in Figure 3 (B). Uncertainty is represented by standard deviation (Mg C/ha) and shows values throughout Catalonia ranging from 0.005 to 0.24 Mg C/ha. Areas with the lowest uncertainty values mainly correspond to fruit orchards in the pre-Pyrenees and the central valley, and to vineyards and nut orchards in southern Catalonia. The highest uncertainty values correspond to olive groves throughout the study area and adult fruit orchards in NE Pyrenees and pre-Pyrenees.

Spatial distribution of carbon density (Mg C/ha) and uncertainty values for each woody crop can be found in Figure A.4. of Appendix A.

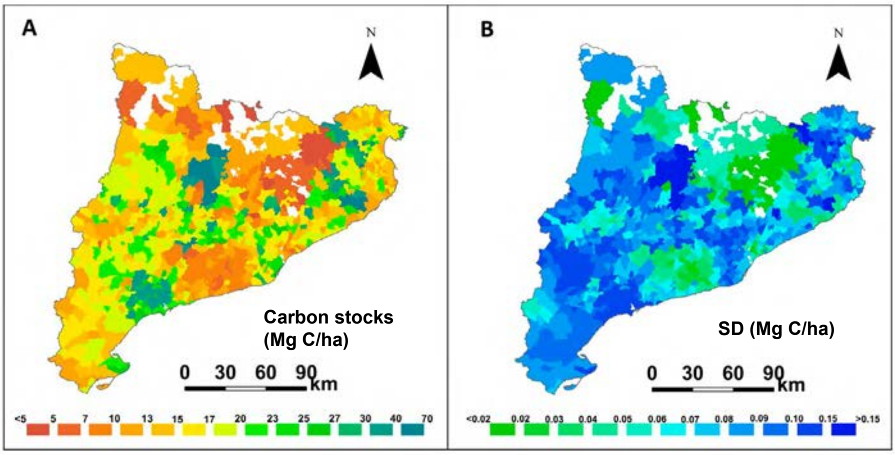

Figure 3. Spatial distribution of (A) average carbon density (Mg C/ha) in the biomass of total woody crops in Catalonia for the year 2013 and (B) uncertainty (standard deviation, SD) of the estimations.

3.3 Carbon stock changes in 2013-2019

The net carbon stock change in Catalonia amounted to +0.173 Tg C/year and +1.040 Tg C in 6 years, representing an annual increase of +3.8%/year and 19% in 6 years.

The entire range of values of this change in Catalonia for each crop type was positive as well, excepting citrus, despite being negative in terms of area for some crop types (Table 2). This upward trend for carbon stock applies to most of the study area, with just a few areas, mainly those with olive and fruit trees, recording a decrease in carbon stocks during this period (Fig. 4).

Carbon stock increases were mainly due to tree growth and the corresponding increases in carbon density (Mg C/ha). This general increase occurred despite decreases in the total woody crop area (-1,681.4 ha/year) throughout the study area (Fig. A.5. of Appendix A), mainly due to decreases in fruit and olive grove areas through the period 2013-2019 (Table 2). The land use change matrix can be found in Appendix B (Table B.8).

Table 2. Carbon stocks and changes in woody crops in Catalonia in 2013-2019. Carbon stock changes are expressed as an annual rate and the number in brackets is the percentage of change per year.

	2013			2019			Change 2013-2019		
Crops	**Tg C**	**Mg C/ha**	**ha**	**Tg C**	**Mg C/ha**	**ha**	**Tg C/year (%)**	**Mg C/ha/year (%)**	**ha/year (%)**
Citrus	0.24	25.95	9,346	0.23	27.25	8,517	-0.002 (-0.72)	+0.22 (+0.8)	-138 (-1.5)
Nuts	1.53	27.40	55,893	1.63	29.09	56,140	+0.017 (+1.10)	+0.28 (+1.0)	+41 (+0.1)
Fruits	1.21	13.86	87,134	1.42	17.80	79,726	+0.035 (+2.92)	+0.66 (+4.7)	-1,235 (-1.4)
Olive	2.14	17.09	125,441	2.79	23.01	121,408	+0.108 (+5.06)	+0.99 (+5.8)	-672 (-0.5)
Grapevine	0.36	6.40	55,612	0.44	7.70	57,546	+0.014 (+4.06)	+0.22 (+3.4)	322 (+0.6)
Total Woody Crops	**5. 48**	**16.44**	**333,426**	**6.52**	**20.17**	**323,337**	**+0.173 (+3.16)**	**+0.62 (+3.8)**	**-1,681 (-2.8)**

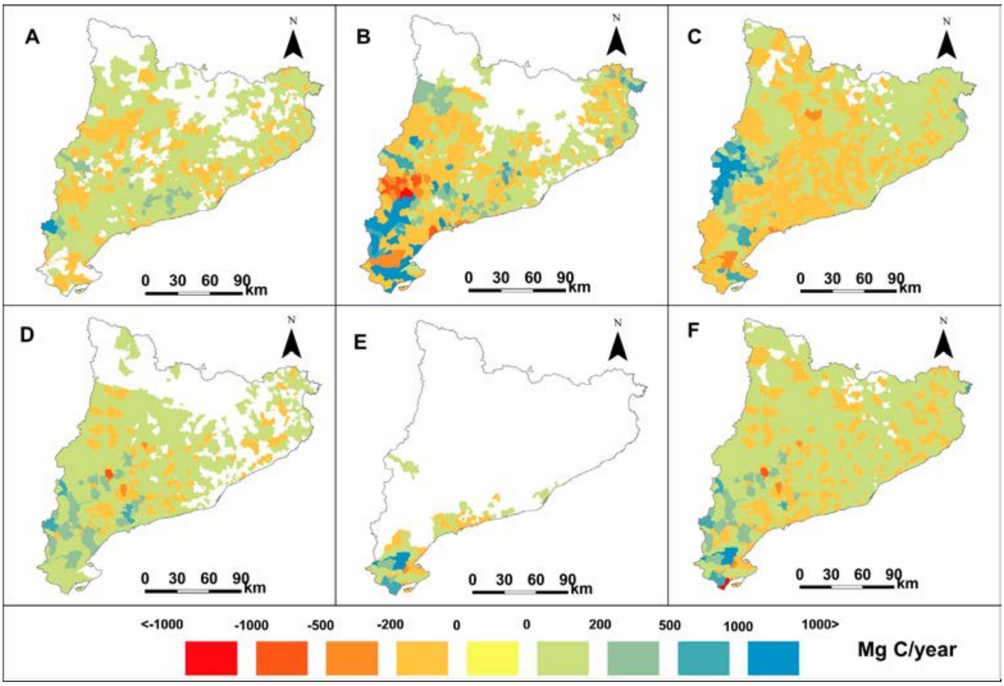

Figure 4. Spatial distribution of total carbon stock change for woody crops in Catalonia from 2013 to 2019 (Mg C/year): A) Grapevine, B) Olive, C) Fruits, D) Nuts, E) Citrus and F) Total woody crops.

4. Discussion

This paper represents the first study to estimate woody cropland carbon stocks, their uncertainties and changes in NE Spain during the 2010s. It considers above and belowground biomass based on unedited data from destructive and non-destructive methods, augmented with literature data.

4.1 Estimating individual carbon stock: crop-specific equations

Eight crop-specific equations were performed to directly or indirectly estimate biomass. Some general or less specific allometries and carbon factors had to be used due to the lack of information in this procedure. The Intergovernmental Panel on Climate Change (IPCC) has classified the methodological approaches in three different Tiers, according to the quantity of information required and the degree of analytical complexity (IPCC, 2006). The approach of our assessment could be defined as Tier 2, since region-specific estimates of biomass stocks by major cropland types and manegement systems were considered. The IPCC Tier 1 global estimate for above and belowground biomass of agricultural land was 5 Mg C/ha (Zomer et al., 2016). Our results show that existing woody cropland in Catalonia makes a greater contribution to the carbon pool than the IPCC Tier 1 estimation. The total carbon estimate for woody cropland is more than twice as high for fruit orchards, more than three times higher for olive, and more than five times higher for citrus and nuts in comparison with the IPCC default value. Only the carbon density estimated here for vines (6.40 Mg C/ha) is close to the IPCC value.

4.2 Carbon stock upscaling and uncertainties

Carbon density estimates in this study are totally in line with the few studies published to date that assess the sequestration potential of woody crops. Badalamenti et al. (2019) reported carbon stocks (ABGB) of 6 Mg C/ha in vineyards on a Mediterranean island (Italy). However, Williams et al. (2011) estimated 3 ± 0.48 Mg C/

ha for ABGB of vineyards and Keightley (2011) 4.15 Mg C/ha (134 Mg C in 32.3 ha) for total perennial vine biomass in California. For citrus, Iglesias et al. (2013) published values ranging from 55 to 66 kg C/tree and 27.5-33.0 Mg C/ha in a 12-year-old plantation with 500 trees/ha in Eastern Spain. Higher ABGB C stock potential was found for plantations in the tropics, such as palm oil, cocoa, orange and rubber, with values of 45, 65, 76 and 214 Mg C/ha, respectively (Kongsager et al., 2013). A mean value of 55.12 Mg C/ha was reported for coffee agroecosystems in Mexico (Ortiz-Ceballos et al., 2020). Similar values were published for ABGB (17 Mg C/ha) and BGB (5 Mg C/ha) in tree cover of an agricultural mosaic in Kenya (Kuyah et al., 2012a, b) and in temperate fruit crops (ranging from 1.5 to 61 Mg C/ha) in the Trans-Himalayan region (Kumar et al., 2010). Carbon stocks of an agroforestry cocoa system in Ghana ranged from 27.1 to 49.1 Mg C/ha in conventional and organic crop management (Asigbaase et al., 2021). At the global level, Zomer et al. (2016) reported 28 Mg C/ha in 2000 and 29 Mg C/ha in 2010, and in particular, 9.3 and 9.4 Mg C/ha in Europe for agroforestry and tree cover on agricultural land, values in line with those published in this study.

Higher values for forest systems have often been reported in literature, but on occasions they have been close or relatively close to those estimated here for Mediterranean woody crops. ABGB carbon stocks of high maquis, maquis forest, forest maquis and Mediterranean old-growth forest on a Mediterranean island (Italy) were published by Badalamenti et al. (2019), showing values of 15, 35, 55 and 105 Mg C/ha, respectively. ABGB of Mediterranean shrubs in Spain were quantified by Pasalodos-Tato et al. (2015), showing values of 12.40 and 10.42 Mg C/ha for formations of heathers and large Cistaceae, respectively, considering 49.60% as the mean value of carbon content for the shrub formations studied. Forest carbon stocks were reported for the western Mediterranean by Vayreda et al. (2012a), showing an average stand C stock (trees + understory) of 45.1 Mg C/ha, ranging from 41.8 to 48.5 Mg C/ha for conifers and broadleaves, respectively, including ABGB and BGB. Other carbon stock values (ABGB + BGB) were reported in terms of equivalent CO_2 (1g C= 3.67g CO_2) for Mediterranean mountain range forest (Herrero and Bravo, 2012). Values of 43.1 and 43.4 Mg C/ha were published for

P. sylvestris and 40.5 and 33.6 Mg C/ha for P. pinaster in two forest regions. The average ABGB carbon density for California wildland ecosystems in 2010 was 26 ± 7 Mg C/ha according to Gonzalez et al. (2015).

In terms of annual carbon sequestration rates, some studies have reported similar values to those estimated here. Annual rates for citrus ranged from 2.8 to 3.3 Mg C/ha/year (Iglesias et al., 2013; Quiñones et al., 2013). For vineyards in Spain, Miranda et al. (2017) found a rate of 0.3 Mg C/ha/year (0.95 Mg CO_2eq /ha/year) for permanent living vine structures. Higher values (from 5.72 to 7.23 Mg C/ha) were reported by Brunori et al. (2016) in a 10-year-old vineyard plantation with 5,600 vines/ha in central Italy. Otherwise, the annual carbon sequestration rates reported here are values very close to those reported in terms of CO_2eq (1g C= 3.67 g CO_2eq) by Aguilera et al. (2015) as annual GHGs emissions from agricultural activities in conventional fruit orchards (ranging from 964 to 6,324 kg CO_2eq/ha/year, i.e., from 0.26 to 1.72 Mg C/ha/year). Therefore, carbon sequestration from biomass of permanent structures, as well as from soils, should be considered in the carbon cycle balance and life-cycle assessments for woody crops.

According to the carbon stock and sequestration values reviewed above, Mediterranean woody crops presented similar values or at least values of the same magnitude as other woody systems or even forest. Consequently, woody crops should be considered in mitigation and land management strategies and policies due to their potential as a carbon sink of their living biomass and, of course, their soils, which was defined in COP21, promoting the 4x1000 strategy (Minasny et al., 2017), and in COP22, showing the importance of woody crops such as olive groves. In this respect, land use change from forest to woody crops may release GHGs in the short term, but these practices could increase carbon storage in specific areas in the long term, for example, by avoiding the potential increase in wildfire frequency due to climate change (Gonzalez et al., 2015).

4.3 LUC effects on carbon stocks

Our findings on carbon stock increase in woody cropland could indicate a turning point in the trend towards a fall in carbon stocks as a direct consequence of the decreasing use of woody cropland in favor of other urban and agricultural uses, principally grassland and arable land. Conversion of woody cropland to grassland and arable land is mainly aimed at agricultural intensification and feeding the meat industry in the study area, leading to high consumption of land and water resources and high GHGs emissions (Vanham et al., 2016). In this context, the use of woody crops becomes important in order to avoid the above-mentioned problems and maintain agricultural productivity, economic stability, mitigation strategies and, consequently, population and the landscape.

The LUC observed in the study area would appear to be a direct response to changing market needs, rather than a country strategy focused on food security and CC mitigation and adaptation. Some examples are: i) the increase in the area occupied by vineyards due to the expansion of the wine sector in recent decades in view of the higher added value of wine and cava, ii) the smaller area devoted to citrus due to soil salinization, irregular spring cold stress and the low prices offered by the global market (South and North Africa), which economically endanger production in the EU, and iii) the increase in the area devoted to high-yielding almond trees in the irrigated area of the central valley (Urgell and Segarra-Garrigues channels), which would appear to be directly related with rising almond prices and speculation in water markets.

If no mitigation and adaptation strategies are considered in territorial management, there will be a trend towards a decrease in woody cropland (mainly rainfed crops) in the study area and consequently an inevitable decrease in the C pool, together with the loss of a significant element of Catalonia's landscape, society, culture and agrobiodiversity.

A suite of cropland management strategies for the Mediterranean, including conservation of high-biomass cropland and the incorporation of woody crops in new areas to aid wildfire management, may be necessary in order to meet goals for the near future in the study area. In fact, carbon stock losses from wildfires could potentially exceed carbon sequestration at a local scale in Mediterranean forest ecosystems (Gonzalez et al., 2015; MedECC, 2020).

4.4 Limitations

Some limitations in this study must be recognized. Firstly, although in general the equations performed were based on fairly good representative and even site-specific data for Mediterranean climates, the lack of specific allometries for olive and nuts in order to estimate biomass based on trunk diameter or basal area is a significant limitation. Allometries based on forest species (Montero et al., 2005) were used for nuts, whereas allometries for young olive trees were employed for olives (Villalobos et al., 2006). Therefore, further efforts are required to improve the estimates by collecting site- and crop-specific data and refining the modeling.

With respect to upscaling, several limitations must be recognized. Firstly, it is possible that carbon stocks are being underestimated, given that crop areas with ages outside the range in the crop-specific equations were assigned carbon stocks corresponding to the oldest age presented in the equation. Important underestimations here could affect citrus and nut carbon stock estimation due to the low representativity of the range of ages in the equation performed for the entire spatial distribution of crop age in the study area (Table B.9 of Appendix B). Secondly, many assumptions about crop traits such as age and plant density distribution had to be made for the study area due to the lack of a specific agricultural census for olive and nuts.

Finally, a few sources of error could not be taken into account in the uncertainty analysis. Although the error in allometric estimates of biomass for olive and nuts was considered in error propagation of the prediction, it was not possible to obtain the error associated with using these non-specific allometries. Moreover, no error was available for agricultural census and SIGPAC to consider in error propagation.

4.5 Implications for policy and future research

The estimation of carbon stocks produced in this study may assist in assessing carbon storage as an ecosystem service in Mediterranean woody cropland for mitigating CC. In this respect, the results could serve as a baseline for shaping policy and considering land management issues through assessment of cropland mitigation potential by spatial analysis based on empirical data. As Williams et al. (2011) noted in the case of California at the beginning of the last decade, most regulation and policies were focused on emissions. Moreover, carbon sequestration was only proposed under the categories of reforestation, improved forest management or avoided conversion. However, these results offer new management possibilities, considering C stocks together with other ecosystem services. Future research should focus on (i) improving carbon stock estimations in woody crops, and (ii) spatial analysis by testing mitigation strategies and land use scenarios using these estimations as a baseline, together with soil carbon stocks (Funes et al., 2019).

5. Conclusion

Our results provide spatial estimates of carbon stock biomass and uncertainties for woodland crops in Catalonia and an analysis of the changes that occurred in the period 2013-2019. The findings from this study can help to quantify the carbon consequences of land management more reliably and to assess the ecosystem services of carbon storage in woody cropland in mitigating climate change.

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Chapter 3

Agricultural soil organic carbon stocks in the north-eastern Iberian Peninsula: drivers and spatial varibility

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Highlights

- SOC stocks were modelled using legacy data, environmental factors and geostatistics.
- The importance of SOC stock drivers differed in the top and subsoil.
- Effects of drivers on agricultural SOC stocks vary spatially at the regional scale.
- SOC stocks in Catalan agricultural soils contain 4.88 ± 0.89 kg/m^2.
- A baseline framework was established to design climate change mitigation strategies.

Keywords

Agricultural SOC stocks; mitigation strategies; Generalized Least Square; Geographical Weighted Regression; Mediterranean agriculture

Abstract

Estimating soil organic carbon (SOC) stocks under agriculture, assessing the importance of their drivers and understanding the spatial distribution of SOC stocks are crucial to predicting possible future SOC stocks scenarios under climate change conditions and to designing appropriate mitigation and adaptation strategies. This study characterized and modelled SOC stocks at two soil depth intervals, topsoil (0-30 cm) and subsoil (30-100 cm), based on both legacy and recent data from 7,245 agricultural soil profiles and using environmental drivers (climate, agricultural practices and soil properties) for agricultural soils in Catalonia (NE Spain). Generalized Least Square (GLS) and Geographical Weighted Regression (GWR) were used as modelling approaches to: (i) assess the main SOC stock drivers and their effects on SOC stocks; (ii) analyse spatial variability of SOC stocks and their relationships with the main drivers; and (iii) predict and map SOC stocks at the regional scale. While topsoil variation of SOC stocks depended mainly on climate, soil texture and agricultural variables, subsoil SOC stocks changes depended mainly on soil attributes such us soil texture, clay content, soil type or depth to bedrock. The GWR model revealed that the relationship between SOC stocks and drivers varied spatially. Finally, the study was only able to predict and map topsoil SOC stocks at the regional scale, because controlling factors of SOC stocks at the subsoil level were largely unavailable for digital mapping. According to the resulting map, the mean SOC stock value for Catalan agriculture at the topsoil level was 4.88 ± 0.89 kg/m^2 and the total magnitude of the carbon pool in agricultural soils of Catalonia up to 30 cm reached 47.9 Tg. The present study findings are useful for defining carbon sequestration strategies at the regional scale related with agricultural land use changes and agricultural management practices in a context of climate change.

1. Introduction

Soils are the largest carbon (C) terrestrial sink at global level, containing approximately 1500 Pg C at 1 m depth (Batjes, 2014), and the C stored exceeds that stored in plant biomass and the atmosphere (Vicente-Vicente et al., 2016). However, soils can become a source of atmospheric carbon dioxide (CO_2) depending on, for example, land use or management practices (Smith, 2012). Land use change is the leading cause of soil organic carbon (SOC) depletion at the global scale, while the main current land use change is deforestation for cultivation, particularly in subtropical and tropical countries (Canadell et al., 2007). Overall, in temperate zones, cropland areas lose more than 50% of their original SOC at the topsoil (0-30 cm) in about 25 to 50 years after conversion from natural ecosystems, due to changes in soil temperature, moisture regimes, soil disturbance and erosion (Lal et al., 2011). Compared to their initial status before cultivation, cropland soils covering 40-50% of global land surface (Smith, 2012) have lost about 55 Pg C worldwide (Canadell et al., 2007), but at present they still store an overall pool of 157 Pg C down to 1 m depth (Jobbagy and Jackson, 2000), which is about 10% of the global SOC pool.

Fortunately, agricultural soils can be managed through the implementation of Recommended Management Practices (RMPs) to improve and restore SOC content and soil properties (Lal et al., 2011). In this respect, mitigation strategies such as the '4 per mille Soils for Food Security and Climate', launched at COP21, seek to increase global soil organic matter stock as a compensation for the global emissions of greenhouse gases (GHGs), in this case, by increasing SOC 0.4 per cent per year in the first two meters of soil (Minasny et al., 2017).

Understanding the current spatial distribution of SOC stocks and its main drivers will help to predict SOC stocks changes in future climate change (CC) scenarios and define CC mitigation strategies (Yigini and Panagos, 2016). Many studies have tried to illustrate the influence of environmental drivers on soil properties as a means to understand SOC distribution based on variables such as land use, soil type, parent material, topography and climate (see review in Zhang et al., 2011). It is widely known that climate variables are important drivers of SOC stock: increasing SOC is associated with higher annual precipitation and lower temperature (Fantappie et al., 2011; Hoyle et al., 2016). Soil properties can also affect SOC stocks inasmuch as organic C is stabilized by means of physical protection or chemical mechanisms (Lawrence et al., 2015).

Mediterranean agriculture is characterized by net primary productivity regulated by limiting factors and scarce resources, such as poor water availability, soil disturbance and nutrient deficiencies (Rashid and Ryan, 2004; Torrent, 2005). Limiting net primary productivity in agriculture under Mediterranean conditions consequently reduces SOC stocks in Mediterranean agricultural soils, since C inputs, such us litter, roots or crop residues, are limited. Soil C sequestration occurs if the balance between C inputs and outputs (through emissions from respiration and mineralization) is positive and finally leads to increased SOC stocks. Several meta-analyses have been performed about SOC sequestration (C inputs > C outputs) in Mediterranean agricultural systems (Aguilera et al., 2013; Vicente-Vicente et al., 2016) with reference to land uses and RMPs. A more than likely future climate scenario in the Mediterranean region entails an increase in temperatures linked with a decrease in available soil water content that would negatively affect yields and, consequently, associated soil C inputs. However, although it is widely known that warming increases microbial activity, soil moisture could act as the main driver of soil biomes in Mediterranean environments, limiting SOC losses by microbial mineralization (Alcañiz et al., 2016). At all events, water management (irrigation or soil water harvesting and storage) is critical to the feasibility of the agricultural sector in Mediterranean regions (Montanaro et al., 2017) and the avoidance of SOC losses, since available water for crops increases biomass productivity, turnover of organic matter timing and humus formation (Lal, 2001).

Measure and prediction of SOC stocks has become a key issue in the last few decades, due to the potential impacts of climate change on them. Making accurate predictions in complex systems such as soils is a challenge, because, among other issues, data on soils is very often outdated, limited and fragmented (Chiti et al., 2012; Aksoy et al., 2016). However, there is a wide range of techniques used in predicting and mapping SOC from landscape to national or continental levels (see review in Minasny et al., 2013). Modelling based on experimental data provides opportunities to quantify the impacts of different management practices and future climate change conditions on SOC stocks (Zhang et al., 2016). The definition of a SOC stock baseline (e.g. Lugato et al., 2014a or FAO, 2018) is essential for future evaluations and, particularly in agricultural ecosystems, could contribute to assessment of the starting or ending point of the stock change that may occur after land use changes (Chiti et al., 2012) or after the establishment of certain RMPs. Moreover, mapping SOC stocks based on dynamic drivers, such as crop type, management or climate, and static drivers such as soil properties or topography would contribute to a better understanding of the spatial pattern of SOC stocks in agricultural Mediterranean soils

To date, other SOC stock assessments have been performed for soils under agriculture in the study area (national level: Rodriguez-Martin et al., 2016 and sub-national level: Alvaro-Fuentes et al., 2011), but the present study focuses particularly on SOC stocks in agricultural soils based on a database containing data from a large number of agricultural soil profiles, with a high density of sampling points, distributed throughout the study area. Moreover, the present study provides the first assessment of agricultural SOC stocks in topsoil (first 30 cm) and subsoil (30 cm to 100 cm) while considering the main SOC drivers for Catalonia (32,108 km^2 NE Spain), a region that is representative of the diverse Mediterranean agricultural systems. In the present study, geostatistical techniques were applied to model SOC stocks for agricultural soils in the study area based on legacy data from 7,245 agricultural soil profiles.

The main objectives of this study were: i) to assess SOC stocks at two depth intervals (top and subsoil) in soil profile; ii) to identify the main explanatory variables driving SOC stocks at the regional scale; iii) to analyse the spatial variability of relationships between SOC stocks and drivers; and iv) to map SOC stocks at the regional scale using a subset of explanatory variables (climatic, topographic and agricultural management).

2. Material and Methods

2.1 Study Area

The study area is limited to agricultural soils in the north-eastern Iberian Peninsula (Catalonia, Fig. 2). According to SIGPAC (2016), the Agricultural Plots Geographical Information System for the year 2016, the cropland area in Catalonia is about 8,837 km^2, not including pastures (340 km^2) and abandoned cropland (639 km^2). Almost 67% of the cropland area remains under rainfed conditions (Fig. 2). Arable land is the most widespread cropland, representing 61% of cropland area, followed by woody crops: Orchard category (17%), Olives (15%) and Vineyard (6%). Agricultural land uses extension in km2 is shown in the stacked bar graph of Figure 2, with its spatial distribution in Figure 3. Catalonia presents Mediterranean climatic conditions characterized by mild winters and hot and dry summers (Terradas and Savé, 1992), but diverse meso- and micro-climates can be found. A strong climatic gradient (Martin-Vide et al., 2016) is defined by mean annual temperature (ranging from 0 to 17.3 °C) and annual precipitation (from 1,464 mm in the Pyrenees to 335 mm in the Ebro Valley). Moreover, a marked continentality gradient is presented between inland (W) and coast (E). See more details in Figure A.1.

Agriculture in the study area is mainly developed over Inceptisols and Entisols (mainly Fluvents and Orthents) and, to a much lesser extent, over Alfisols, Aridisols and Mollisols (SSS, 2014). Inceptisols (medium-poorly developed soils) over calcareous substrates and Entisols (very poorly developed soils) cover most of the study area. Aridisols are typical of areas where evapotranspiration is higher than precipitation, limiting crop production except when irrigation is applied, in which case high yields are obtained. Aridisols are mainly located in the Ebro valley, a historically irrigated cropland area. Agricultural soils are mostly medium (loamy) textured, with a basic reaction. Calcium carbonate-rich soils are dominant, often with a petrocalcic horizon as a root-limiting layer. Salinity problems occur over significant areas in the Ebro Valley and river deltas.

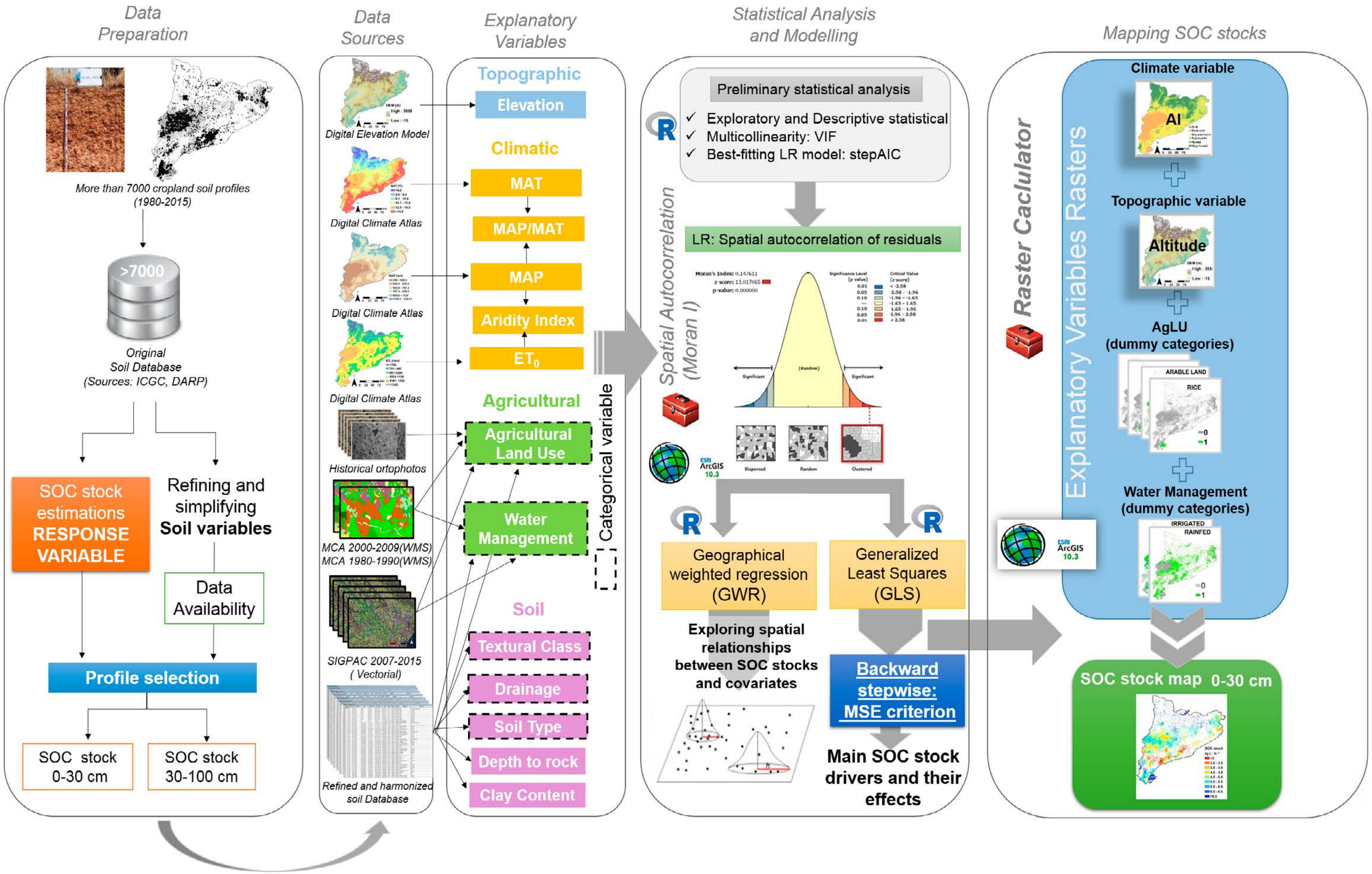

Figure 1. Methodology flowchart: data, data sources, modelling framework and mapping. Climatic variables are mean annual temperature (MAT, ºC), mean annual precipitation (MAP, mm), aridity index (AI, dimensionless), MAP/MAT ratio, mean annual evapotranspiration (ET0, mm). Sources of both agricultural variables, Agricultural land use (AgLU) and Water Management, are: i) two editions of the map of crops and land uses (MCA, acronym in Spanish) via web map service (WMS); ii) the Agricultural Plots Geographical Information System (SIGPAC, acronym in Spanish) from the year 2007 to 2016, iii) historical ortophotos (ICGC) and iv) the original soil database. Name abbreviations in the preliminary statistical analysis: Linear Regression (LR), Mean Square Error (MSE) and Variance Inflation Factors (VIF). Figure inspired by Luo et al. (2017).

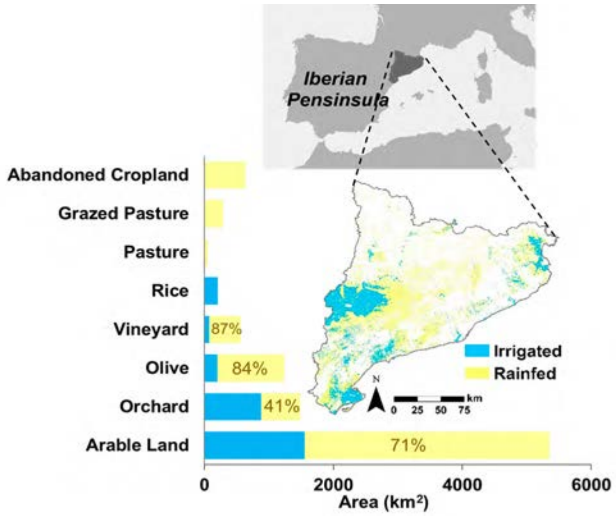

Figure 2. Location of the study area.

The map represents the spatial distribution of agricultural water management based on SIGPAC (2016) and DUN (2016). Area (km^2) per agricultural land use category is represented in the stacked bar graph; a distinction is drawn between irrigated (blue bars) and rainfed (yellow bars). Numbers within bars show the percentage of the rainfed area for each category presenting both irrigated and rainfed systems.

2.2 Data harmonization and SOC stock estimations

Data collection

Soil data has been obtained from: i) the Soil database of Catalonia (BDSisCat; ICGC, 2018) of the Cartographic and Geological Institute of Catalonia (ICGC, acronym in Catalan) and ii) soil data of the Department of Agriculture, Livestock, Fisheries, Food and Environment of the Catalan Government (DARP, acronym in Catalan). Most of this data is derived from the soil survey for the Soil Map of Catalonia 1:25000 (MSC25M; ICGC, 2017).

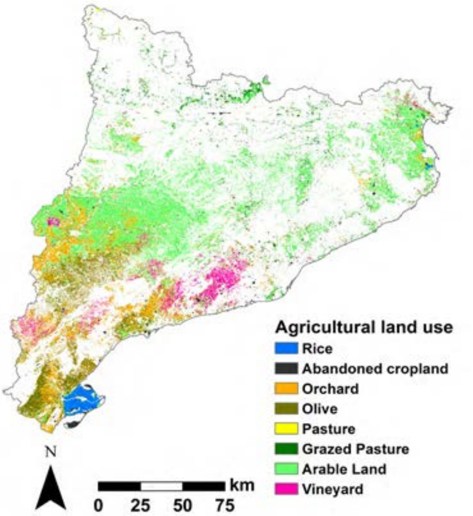

Figure 3. Spatial distribution of agricultural land use categories based on SIGPAC (2016) and DUN (2016).

The initial dataset included data of 7,245 soil profiles, acquired from 1980 to 2015.

SOC stock estimations

SOC stocks were estimated for two depth intervals through the vertical soil profile: standard depth intervals for topsoil (0-30 cm) and subsoil (30-100 cm). For a given horizon, the SOC stock, in kg/m^2, was calculated as follows:

$$\text{SOC} = \text{Bd} \cdot (\text{OCc} / 100) \cdot 10000 \cdot \text{Th} \cdot (1 - \text{S}) \cdot (1 / 1000) \qquad \textbf{Eq. 1}$$

where Bd is bulk density (g · cm^{-3}), OCc the concentration of OC in the fine earth (as % w/w), Th stands for the thickness of the horizon in cm, and S the stoniness (dimensionless), understood as the fraction of horizon volume (0 to 1) occupied by gravel and stones. Whereas stoniness was estimated visually in the field during soil profile description and sampling, bulk density is rarely measured in the field, and it was approached by a pedotransfer function (Honeysett and Ratkowski, 1989). The total SOC stock of a given profile is the cumulative sum of the SOC stocks in the individual horizons, down to the desired depth.

Often this depth (either 30 or 100 cm) does not match the lowermost limit of any horizon. In such a case, it is necessary to apply a correction factor for the stock of the last horizon. Let us assume that the soil has n horizons, and that the last one is divided by two by this desired depth, d_D. The total cumulative SOC stock, SOC_C, will be:

$$\text{SOC}_\text{C} = \left(\sum_{i=1}^{n-1} \text{SOC}_\text{i}\right) + \left(\text{SOC}_\text{n} \cdot \frac{d_D - d_{Un}}{d_{Ln} - d_{Un}}\right) \qquad \textbf{Eq. 2}$$

where SOC_C is the cumulative sum of the SOC stocks of all horizons down to the desired depth (either 30 or 100 cm), n stands for the horizon number which is divided by two by the desired depth, d_D indicates the desired limit, d_{Un} is the depth of the upper limit of this horizon, and d_{Ln} is the depth of the lower limit of this horizon.

Data selection

Profiles were excluded if data of one or more of the explanatory variables was missing (mainly soil properties; listed in Figure 1) or if data needed to estimate SOC stocks was missing, as well. The deeper the lower limit of the depth interval, the fewer the number of profiles contained in the dataset, for usually only top horizons were analysed in soil site legacy data on organic matter and other soil properties. Spatial distribution of profiles' final dataset for each horizon (top and subsoil) is shown, respectively, in Figure A.2.

2.3 Explanatory variables

A set of climatic (MAT, MAP, MAP/MAT, ET_0, AI; see definition of abbreviations in Figure 1 caption), topographic (altitude), agricultural (land use and water management) and soil variables (soil texture, soil type, soil drainage, clay content and depth to bedrock) was used as potential explanatory variables for modelling SOC stocks (listed in the Explanatory Variables section of the methodology flowchart in Figure 1). Detailed information about explanatory variables and their sources are explained in Appendix B of methodology.

2.4 Statistical analyses and modelling

Statistical and modelling analysis of the SOC stock data was conducted using the R software (R Development Core Team, 2014) and ArcGIS 10.3. (ESRI, 2011). In the analysis, the steps described below were followed:

1. Firstly, a descriptive statistics analysis (i.e. mean and standard deviation) of SOC stock data was carried out to characterize our datasets (Table 1). The results were aggregated by levels of the categorical explanatory variables.

2. Next, a preliminary visual inspection of the relationships between response and explanatory variables was performed. A careful assessment of these relationships led us to apply a square-root transformation of the SOC stock data to reduce or eliminate the

impact of any heteroscedastic errors present in the data.

3. We then applied analysis-of-variance (ANOVA) to check for significant differences among the mean values of the square-root-transformed SOC stock data. To further test whether there existed significant pair-wise differences we used a post-hoc Tukey HSD test.

Table 1. Descriptive statistics (Mean and SD) of SOC stock corresponding to 0-30 cm and 30-100 cm depth intervals, with data sets aggregated for categorical variables: agricultural land use category, water management, profile drainage, profile textural class and soil type. Relative SOC stock (%) of topsoil (0-30 cm) with respect to the first meter (0-100 cm).

	0-30 cm (2816 profiles)			30-100 cm (1612 profiles)			Relative SOC Stock
Cropland category	n	Mean SOC (kg/m^2) ± SD	*	n	Mean SOC (kg/m^2) ± SD	*	% 0-30 cm:0-100 cm
Grazed Pasture	141	6.92 ± 2.74	a	79	4.52 ± 2.81	d	58
Rice	49	6.45 ± 1.56	a	46	8.17 ± 5.15	a	44.3
Abandoned agriculture land	281	5.07 ± 1.78	b	140	6.32 ± 4.23	b	43.3
Pasture	38	4.88 ± 1.86	bc	25	4.70 ± 2.80	cd	51
Orchard	488	4.69 ±1.59	bc	248	5.65 ± 3.01	bc	46.1
Arable land	1288	4.62 ± 1.62	c	808	6.02 ± 2.76	b	44.3
Olive	298	4.60 ± 1.37	c	152	5.13 ± 3.30	cd	44.8
Vineyard	233	3.57 ± 1.65	d	114	5.30 ± 2.61	bcd	42.3
Water management regime							
Irrigated	413	5.03 ± 1.60	a	262	6.20 ± 3.35	a	44.8
Rainfed	2403	4.68 ± 1.75	b	1350	5.75 ± 3.09	b	44.9
Profile Drainage							
Poor	123	5.83 ± 1.95	a	86	7.75 ± 5.74	a	42.9
Excessive	117	4.84 ± 1.69	b	51	4.16 ± 2.93	c	53.8
Average	180	4.79 ± 1.78	b	129	5.45 ± 2.56	b	46.8
Good	2396	4.67 ± 1.70	b	1346	5.80 ± 2.90	b	44.6
Profile Textural Class							
Fine	23	5.88 ± 1.91	a	12	7.58 ± 2.40	a	43.7
Medium-Fine	462	5.30 ± 1.79	a	295	6.93 ± 3.92	a	43.3
Medium	1891	4.72 ± 1.60	b	1091	5.75 ± 2.67	a	45.1
Medium-Coarse	413	4.22 ± 1.94	c	198	4.58 ± 3.65	b	48.0
Coarse	27	2.86 ± 1.69	d	16	4.24 ± 3.29	b	40.3
Soil Type							
Mollisol	200	5.65 ± 2.13	a	88	4.81 ± 3.60	c	54.0
Aridisol	39	4.77 ± 1.44	ab	11	3.08 ± 2.01	c	60.8
Entisol	1009	4.69 ± 1.65	b	651	6.50 ± 3.27	a	41.9
Inceptisol	1473	4.66 ± 1.70	b	808	5.47 ± 3.86	b	46.0
Alfisol	95	4.43 ± 1.53	b	54	5.21 ± 3.29	bc	46.0

* Same letter indicates no significant differences ($p<0.05$) and different letter indicates differences between groups ($p<0.05$) tested by ANOVA of square root transformed SOC stock values. SD: standard deviation, n: number of profiles.

4. A linear regression (LR) was subsequently performed to assess the predictive power of the selected set of explanatory variables, to measure the presence of collinearity effects between them and, finally, to investigate the existence of spatial correlation in the residuals of the fit. The LR model was separately applied to the square-root-transformed top and subsoil SOC stock datasets. The starting set of explanatory variables included environmental, pedological and agricultural drivers. Once the LR model had been computed, variance inflation factors (VIFs) of the continuous explanatory variables included in the model (vif function in the "car" R package) were calculated to evaluate the absence of collinearity, before proceeding to eliminate those variables whose VIF was greater than 2 (i.e. moderately to highly correlated). Next, a backward stepwise model selection strategy with all the remaining variables for both top and subsoil datasets was performed, choosing the model with the lowest Akaike information criterion (stepAIC function of the "MASS" R package).

5. The residuals at every spatial location from the resulting best LR models were then determined and the corresponding Moran index was calculated (Rangel et al., 2006) using ArcGIS 10.3 for both top and subsoil datasets.

6. Once the Moran index analysis confirmed the presence of spatial correlation of residuals (For topsoil database, Moran's Index= 0.138; z-score=12.173; $p<0.01$ and, for subsoil database, Moran's Index=0.095; z-score=4.438; $p<0.01$), their spatial correlation structure was explicitly modelled with the aid of a General Least Squares (GLS) analysis (gls function of the "nlme" R package). GLS is a regression technique by which the spatial component of the residual term is explicitly modelled in the variance-covariance matrix using parametric functions (Gaussian, exponential, lineal, etc.). In our case, GLS included X-Y site coordinates in the random-effect part of the model. Prior to the GLS calculations, data sets were partitioned into training and test subsets, containing 70% and 30% of data points, respectively. Next, backward stepwise model selection was performed, starting once again from a full model and employing the training subset for the calculations of parameter estimates. We instructed the backward stepwise procedure to remove only one or

two variables at each step, due to limitations in available computing power. The criterion for model selection was mean square error (MSE), so the lower the MSE between the test data points and their corresponding predicted values (the latter determined with the parameter estimates from the model selection step), the better the model. For the spatial covariance part of the GLS model, an exponential correlation structure was chosen, which satisfactorily accounted for distance-decay effects. With the help of GLS outputs, the proportional contribution that each remaining explanatory variable made to the R^2 coefficient was calculated. In addition, the significance of each predictor based on the p-value of the ANOVA of best-fitting model and the relative importance of variables (RIV) in explaining variation in SOC stocks were assessed. In order to rank controlling factors of SOC stocks, the RIV of each variable was assessed as the % of the difference between the R^2 from the best-fitting model and the R^2 from the model removing each variable.

7. To further understand how the relationship between SOC stock and the explanatory variables changes spatially, a geographically weighted regression (GWR; Fotheringham and Oshan; 2016) was also performed. The GWR technique can be used to show the spatial variation of parameter estimates, which are determined locally rather than globally with a weighted least squares scheme. These weights are specified so that closer points have more influence on the determination of a local parameter than points located further away. Considering that soil samples in the present study were not regularly distributed in space, as a weighting function an adaptive spatial Gaussian kernel with a dynamically determined bandwidth was employed. GWR was performed using the same explanatory variables selected previously with the GLS model selection procedure, but this time all data points were included (i.e. without splitting the dataset into training and test subsets). Maps of continuous spatial distribution of a) GWR local estimates, b) local R^2 and c) residuals were generated by kriging interpolation to explore varying spatial relationships between SOC stock values and the main drivers, as well as to evaluate model performance at local and global scales.

To evaluate model performance in predicting SOC stock content, the global coefficient of determination (R^2), Root Mean Square Error (RMSE) and Mean Error (ME) were calculated. These indices were evaluated with the test data set for GLS models and with a complete data set for GWR.

2.5 Mapping SOC stocks

Digital mapping of SOC stocks was performed by applying a regression (GLS) of SOC stocks on spatial data of the environmental variables considered as predictors. Due to problems of unavailability of good spatial resolution for several covariates, such as soil properties, the covariates used in the GLS models for mapping (hereafter, GLSmap) differed from those employed in the GLS models used to assess the predictive power of each driver, as explained in step 6 of the previous section. Therefore, GLS models had to be re-fitted based on a new set of covariates. To apply the GLSmap regression equation, a set of map layers in raster format was used. Spatial data on agricultural covariates (categorical) was converted to dummy rasters (values of either 1 or 0 showing presence or absence of each category, respectively). Spatial data on climatic variables was obtained from the Digital Climatic Atlas of Catalonia and altitude data was drawn from the DEM of Catalonia (same rasters described in Appendix B of extended Material and Methods). Prediction was performed by applying map algebra (through the GLSmap regression equation and the set of covariates maps) using the GIS tool Raster calculator of ArcGIS 10.3.1 (ESRI, 2011). Prediction at the pixel level needed to be corrected by adding kriged residuals (differences between measured and predicted SOC stock at observed locations) from the GLS fit, in order to correct spatial correlation of residuals following Ninyerola et al. (2000). This procedure is also known as Regression Kriging in geostatistics (Chen et al., 2018).

The final corrected SOC stock maps were back-transformed from square-root in order to yield SOC stock values in kg/m^2 units. Spatial resolution was set to 180×180 m, as used in the climatic maps.

3. Results

3.1 Descriptive statistical and depth profile SOC stock distribution

Mean SOC stock values were significantly different ($p<0.05$) for each categorical variable at the topsoil and subsoil (Table 1). Rice showed the highest mean SOC stock at the top and subsoil. Grazed pastures showed the highest mean SOC stock at the topsoil, but the lowest at the subsoil. Vineyard soils showed the lowest value in the topsoil. Irrigated cropland presented higher SOC stocks than rainfed at both top and subsoil. Poor profile drainage was associated to higher SOC stocks in both top and subsoil. With respect to textural classes, higher SOC values were linked to finer textures. Mollisols had the highest SOC stocks at the topsoil, while Entisols had the highest SOC stocks at the subsoil. Averaged values of SOC stock for agricultural land use in soil up to a depth of 1 m were ~10 kg/m^2, ranging from 9.2 to 14.7 kg/m^2, corresponding to vineyard and rice agricultural land use categories, respectively. For all categories, more than 50% of the total stock relative to 1 m depth was located in the subsoil (30-100 cm), except for pastures (especially grazed pasture), excessive drainages, Mollisols and Aridisols (Table 1).

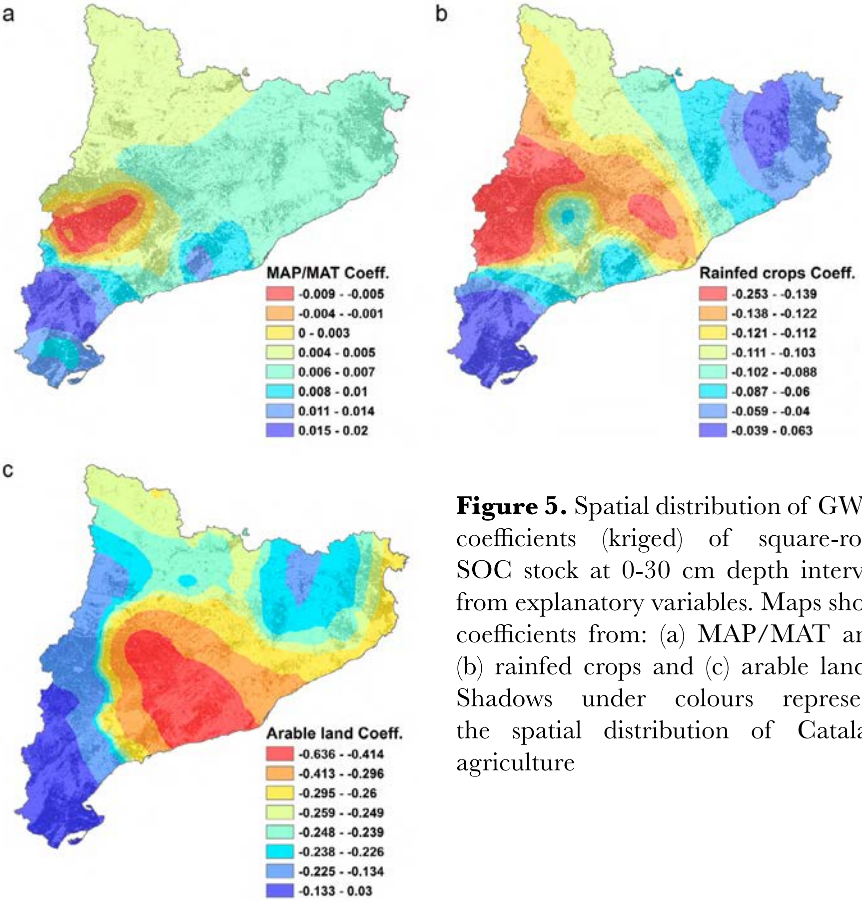

Figure 5. Spatial distribution of GWR coefficients (kriged) of square-root SOC stock at 0-30 cm depth interval from explanatory variables. Maps show coefficients from: (a) MAP/MAT and (b) rainfed crops and (c) arable lands. Shadows under colours represent the spatial distribution of Catalan agriculture

3.2 GLS and GWR modelling, model evaluation and relative importance of explanatory variables

3.2.1 GLS model performance and relative importance of variables

GLS models accounted for 27% and 20% of variations of SOC stocks at the top and subsoil, respectively (Table 2). The negative values of Mean Error (ME) obtained imply that all the prediction models were negatively unbiased, suggesting under prediction. Like R^2, RMSE was lower in the topsoil than in the subsoil. On the one hand, in the GLS model for topsoil significant coefficients of SOC stock (square-root transformed) were found for agricultural land use, water management and textural class. Climate variable MAP/MAT showed a positive relationship with SOC stock. However, clay content presented a significant negative coefficient of SOC stock (square-root transformed). In Figure A.9 (a) we can see how clay content and SOC stock (square-root transformed) at the topsoil were positively correlated up to ~30 kg clay/m^2, and from this point on the relationship presented a slightly negative trend strongly conditioned by higher clay content, making the general trend negative. A drainage factor was not significant in the model, and soil type and soil depth were variables previously dismissed in the backward stepwise performance. On the other hand, the GLS model for subsoil showed significant coefficients for agricultural land use, excessive drainage and soil type (Table 2). Clay content and depth profiles at the subsoil showed a significant positive coefficient of SOC stock (square-root transformed). Water management and MAP/MAT were previously excluded in the backward stepwise performance.

The RIV for SOC stocks differed between top and subsoil (Fig. 4). In order to explain topsoil SOC stocks in the GLS model, textural class was the most important variable, followed by agricultural land use, MAP/MAT ratio, clay content, and finally water management. Soil properties explained 39% of topsoil SOC stock variability, land use and management 18%, and climate 15%. In the subsoil, the depth of the profile had the strongest influence on SOC stocks, followed by soil type, textural class, clay content, agricultural land use and finally drainage. Thus, soil properties explain more than 44% of SOC stock variability at the subsoil, whereas land use accounts for just under 6%.

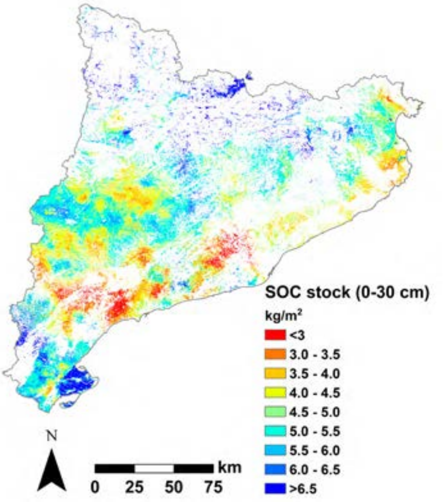

Figure 6. Spatial distribution of predicted soil organic carbon stocks (kg/m^2) in Catalan agricultural soils using GLS performance at 0–30 cm soil depth profile. The areas rendered with white colour are non-agricultural areas.

Table 2. GLS model coefficients of square-root transformed SOC [sqrt SOC kg/m^2], confident intervals (standard error, SE), significance for each variable (based on train data set) and validation statistics (based on test data set) corresponding to 0-30 cm and 30-100 cm depth intervals.

		0-30 cm GLS Model			30-100 cm GLS Model		
		Coefficients ± SE	t value		Coefficients ± SE	t value	
	Intercept	**2.821 ± 0.116**	**24.270**	***	**1.737 ± 0.235**	**7.403**	***
Respect Rice	Abandoned land	**-0.176 ± 0.072**	**-2.433**	*	-0.169 ± 0.129	-1.315	
	Orchard	**-0.215 ± 0.070**	**-3.072**	**	-0.235 ± 0.125	-1.884	.
	Olive	**-0.242 ± 0.073**	**-3.338**	***	**-0.381 ± 0.130**	**-2.938**	**
	Pasture	**-0.309 ± 0.092**	**-3.373**	***	**-0.370 ± 0.166**	**-2.229**	*
	Grazed Pasture	-0.147 ± 0.082	-1.795	.	**-0.403 ± 0.134**	**-3.006**	**
	Arable Land	**-0.267 ± 0.679**	**-3.927**	***	-0.230 ± 0.118	-1.956	.
	Vineyard	**-0.481 ± 0.737**	**-6.519**	***	**-0.356 ± 0.134**	**-2.648**	**
Respect Irrigated	Rainfed	**-0.081 ± 0.024**	**-3.400**	***	-	-	
Respect Fine texture	Coarse	**-1.051 ± 0.112**	**-9.349**	***	-0.279 ± 0.232	-1.203	
	Medium-Fine	**-0.179 ± 0.080**	**-2.251**	*	0.056 ± 0.174	0.324	
	Medium-Coarse	**-0.597 ± 0.087**	**-6.866**	***	-0.334 ± 0.183	-1.831	.
	Medium	**-0.344 ± 0.082**	**-4.222**	***	-0.121 ± 0.174	-0.696	
Respect Good drainage	Poor	0.061 ± 0.040	1.502		0.033 ± 0.085	0.039	
	Excessive	-0.016 ± 0.037	-0.434		-0.102 ± 0.093	-1.092	
	Average	-0.044 ± 0.082	-1.370		**-0.167 ± 0.062**	**-2.710**	**
Respect Alfisol	Aridisol	-	-		-0.194 ± 0.196	-0.989	
	Entisol	-	-		**0.337 ± 0.086**	**3.912**	***
	Inceptisol	-	-		**0.171 ± 0.084**	**2.046**	*
	Mollisol	-	-		0.116 ± 0.113	1.027	
	Depth Profile	-	-		**0.004 ± 0.0006**	**7.077**	***
	Clay content	**-0.002 ± 0.0003**	**-7.176**	***	**0.001 ± 0.0002**	**5.698**	***
	MAP/MAT	**0.005 ± 0.0005**	**10.216**	***	-	-	
Model Evaluation (Test data set)	Degrees of freedom	722			393		
	R^2	0.272			0.203		
	ME	-0.0015			-0.0011		
	RMSE	0.318			0.573		

Reference categories for each categorical predictor are denoted on the left-hand side preceded by the word “Respect”. GLS Model coefficients that are significant are shown in bold. Coefficients of variables excluded for each model in the backward stepwise performance are marked with a hyphen. An asterisk denotes $p<0.05$, a double asterisk $p<0.01$ and a triple asterisk $p<0.001$. A point denotes marginal significance ($p<0.1$).

3.2.2 GWR model performance

GWR global coefficients of SOC stock (square-root transformed) and model evaluation (Table A.2.) were in line with GLS performance (Table 2). GWR coefficients of variables ranged from negative to positive, indicating the existence of spatially varying relationships between SOC stock and their explanatory variables (coefficients from the dynamic variables at the topsoil in Figure 5 and coefficients from the rest of the explanatory variables can be found in SM). GLS and GWR global estimates for the MAP/MAT variable presented a positive sign since the combination of high precipitation and low temperatures is related with high SOC stocks. Positive MAP/MAT coefficients at the topsoil (Fig. 5a) were distributed right across the study area, excluding the Catalan Central Depression, where negative coefficients were obtained. The obvious reason is that, in these areas, irrigation countervails drought, and high levels of plant production are attained. Although local estimates for rainfed crops (Fig. 5b) were negative at the topsoil throughout the study area, the intensity of the relationships was not constant. Rainfed crops presented lower SOC stocks than irrigated right across the study area, with a more marked difference in the Catalan Central Depression. GWR coefficients for all the agricultural land use categories showed a similar spatial pattern at the topsoil (Fig. 5c and Fig. A.3 from b to g): they were negative all over Catalonia, showing the greatest magnitude in the East central areas.

The remaining variable coefficients for top and subsoil varied spatially in magnitude and even sign as well (some examples in Fig. A.3 and Fig. A.5). Higher local R^2 values were observed in northern areas for the topsoil GWR model (Fig. A.4a). In contrast to topsoil, higher local R^2 values were observed in southern zones for subsoil GWR local models (Fig. A.6a). GWR bandwidth sizes (km) were smaller for topsoil (Fig. A.4d) than subsoil (Fig. A.6d) at certain locations due to sample density (small bandwidth size was correlated to high sample density). GWR residuals were randomly spatially distributed from positive (blue colour) to negative (red colour) values at the top (Fig. A.4b) and subsoil (Fig. A.6b).

3.3 Mapping SOC stocks: a baseline map

Coefficients of the GLSmap model were used at the pixel level (180 x 180 m) to predict SOC stocks (Table A.3). Explanatory variables used in the GLSmap model, limited by mapping availability and showing the best-fitting model, were agricultural land use, water management, aridity index and altitude. Correlation coefficients of variables in the GLSmap model matched with those obtained from the GLS model used to assess the predictive power of covariates. The correlation coefficient (R^2) for the topsoil GLSmap model is 0.18. The agricultural soils of northern areas (Pyrenees and Pre-Pyrenees) have relatively higher SOC stocks (> 6.0 kg/m^2) than the rest of the region (Fig. 6). Paddy fields, found in two areas (Ebro Delta and Empordà plain), stood out with high SOC stocks. Moderate SOC stocks (4.0-5.5 kg/m^2) were located in the Ebro valley, southern and north-eastern regions, representing almost 84% of the study area. Soils with lower SOC stocks (< 4.0 kg/m^2) were concentrated along the Pre-Coastal Depression (from central to south), coinciding with some important vineyard and olive growing regions. Residuals of the GLSmap model for SOC stocks at the topsoil showed spatial heterogeneity: negative (red colour) and positive (green colour) residuals, under and over predicting SOC stocks, respectively, were observed (Fig. A.7).

Averaged SOC stock values in the topsoil derived from mapping of Catalonia agriculture ranged from 0.99 to 13.98 kg/m^2 and the mean value was 4.88 ± 0.89 kg/m^2. Estimation of absolute values of SOC stocks for the topsoil total 47.89 Tg for all the agricultural land in the study area (Table 3). Most agricultural land uses (arable land, orchard, olive and abandoned land) presented a gaussian-like distribution of SOC stock classes (i.e. symmetric histograms with most of the surface bunched in the middle SOC stock classes: from 4 to 5.5 kg/m^2), unlike other agricultural land uses that showed left- (rice, pastures and grazed pastures) and right- (vineyard) skewed histograms.

Table 3
Agricultural SOC stocks of Catalonia: mean value of SOC stocks (kg/m^2)and absolute values of SOC pool (1 Tg = 1012 g) aggregated by agricultural land use.

		SOC (0-30 cm)	
Cropland category	**Area (ha)**	**kg/m^2 (mean ± SD^a)**	**Tg (absolute)**
Rice	20,269	7.01 ± 0.62	1.42
Abandoned land	61,693	5.22 ± 1.24	3.22
Orchard	147,750	4.77 ± 0.94	7.04
Olive	123,719	4.70 ± 0.94	5.82
Pastures	5,122	5.87 ± 1.56	0.30
Grazed pastures	33,933	6.90 ± 1.32	2.34
Arable Land	533,651	4.83 ± 0.74	25.80
Vineyard	56,097	3.47 ± 0.86	1.95
Total Cropland	**982,235**	**4.88 ± 0.89**	**47.89**

[a] SD refers to standard deviation of the predicted SOC values at the pixel level aggregated by agricultural land use category.

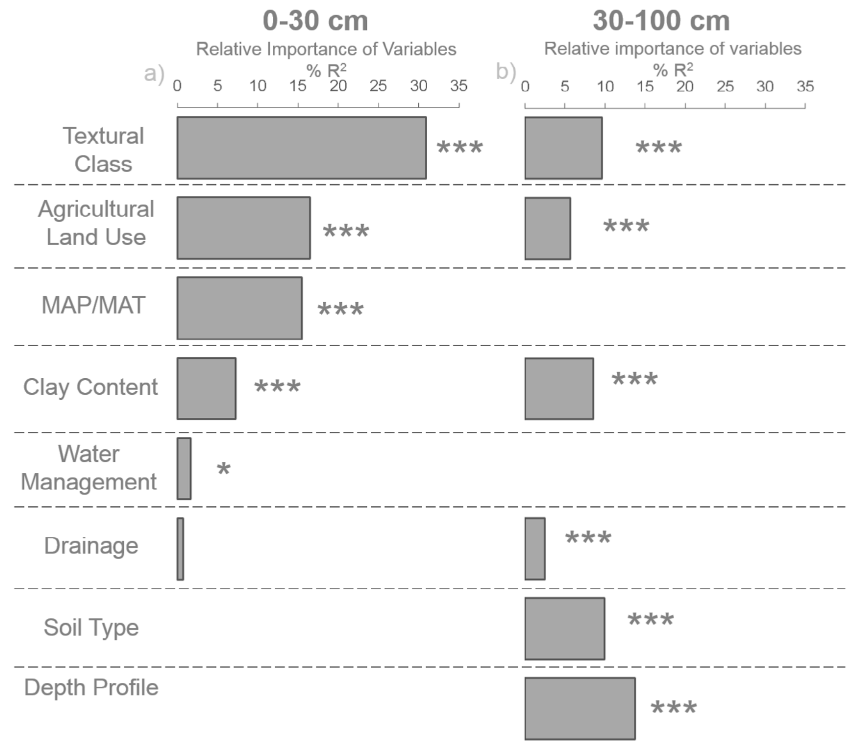

Figure 4. Relative importance of variables (RIV) calculated as proportion of R^2 (train data set) in explaining variation of SOC stocks along a) topsoil: 0-30 cm depth interval and b) subsoil: 30-100 cm depth interval. An asterisk "*" denotes $p<0.05$, a triple asterisk "***" denotes $p<0.001$ and the absence of asterisks denotes no significance. Variables are sorted by relative variable importance in the GLS model set for the topsoil.

4. Discussion

4.1 Characterizing agricultural SOC stocks and its vertical distribution up to 1 m

The mean SOC stock values obtained from both data sets (Table 1) were in line with the previous SOC characterizations or estimations for agricultural soils down to 30 cm in other Mediterranean (Chiti et al., 2012; Rodriguez-Martin et al., 2016; Farina et al., 2017) and non-Mediterranean (Martin et al., 2011; Luo et al., 2013; Liu et al., 2015) regions.

Mean SOC stock values differed substantially from those drawn from studies in non-Mediterranean agricultural systems and other land uses. Higher values were found in agricultural soils at northern or tropical latitudes (Neufeldt, 2005; Adhikari et al., 2014; Bonfatti et al., 2016). Lower SOC stock values have been published for agricultural soils in southern, semi-arid or arid regions (Albaladejo et al., 2013; Hoyle et al., 2016; Chakan et al., 2017; Muñoz-Rojas et al., 2017; Schillaci et al., 2017a). Likewise, lower SOC stock values were estimated in Spanish soils in forest, shrubland and grassland systems estimated at 1 m depth by Doblas-Miranda et al. (2013), perhaps because these land uses are mainly encountered on shallower soils or steep slopes, whereas deeper soils and gentle slopes are preferable used for cultivated fields (Albaladejo et al., 2013; Lacoste et al., 2014) that have a greater capacity to store SOC. Notwithstanding this, when only the first 30 cm were considered, higher mean values were found under forests, shrublands and grasslands in Spain (Rodriguez-Martin et al., 2016).

The present study estimated that more than 50% of the total stock to 1 m depth is located in the subsoil (Table 1). These results are similar to those for soils in other climatically different regions like Iran (Chakan et al., 2017) and NW France (Lacoste et al., 2014), but are in contrast to findings for northern latitudes, where SOC stocks are greater in topsoil (Neufeldt, 2005; Kumar et al., 2013; Adhikari et al., 2014). It is commonly found that soil C generally decreases exponentially with soil depth (Albaladejo et al., 2013; Kumar et al., 2013; Hobley and Wilson, 2016).

4.2 Modelling SOC stocks

The percentage of explained variance obtained by GLS models in this study ranged from 20% to 27%, corresponding to sub and topsoil models, respectively. Higher data density from topsoil might have a positive effect on modelling performance (Adhikari et al., 2014). R^2 for GLS models used to map SOC stocks in the topsoil was lower (R^2=0.18), because several drivers of SOC stock, such as soil properties, could not finally be included due to unavailability of good spatial resolution (Table A.3). In addition, for the very same reason, R^2 of GLS used to map SOC in the subsoil (data not shown) was negligible (R^2= 0.016) and mapping SOC stocks at the subsoil was finally dismissed. Although R^2 values obtained may seem low, values of R^2 higher than 0.7 are in fact unusual, and values <0.5 are common in soil attribute prediction. Moreover, R^2 values usually decrease with depth (see Table 4 and Table A.4; Adhikari et al., 2014; Chakan et al., 2017).

The R^2 values obtained could be associated with heterogeneity of spatial data density or other factors not tested due to data unavailability. Higher R^2 values have been found when different land uses (forest or scrubland) were modelled (Albaladejo et al., 2013).

In order to deal with spatial correlation of residuals, two models were performed: GLS and GWR. Both models are considered robust and have been widely used in statistical literature for decades (Wang and Tenhunen, 2005; Rangel et al., 2006; Luo et al., 2017; Peng et al., 2017). See more references compiled in Table 4 and Table A.4). Here similar results using both methodological approaches were obtained (Table 2 and Table A.2).

4.3 Conclusive factors affecting agricultural SOC stocks

The main drivers of SOC stocks depend on the position in the soil profile (topsoil versus subsoil). At the topsoil, the main drivers were textural class, agricultural land use and MAP/MAT. Soil properties become more relevant with increasing depth. At the subsoil, the agricultural land use category was still important, but MAP/MAT ratio and water management were no longer considered important SOC drivers at depth. In line with the present study findings, some authors (Albaladejo et al., 2013; Bonfatti et al., 2016; Armas et al., 2017; Chen et al., 2018) state that variable importance varies with depth. Climate, land use and management are likely to have a strong influence on SOC stocks at the topsoil, where these drivers directly impact. However, in the subsoil physico-chemical soil attributes are expected to be more crucial as drivers of SOC stocks than environmental factors. The importance of variables in explaining SOC stocks found here concurs with many studies (see Table 4 and Table A.4) where soil properties, climate and land use and management are seen to be the key factors. Several studies have highlighted the importance of climate in predicting SOC stocks (see

Table 4 and Table A.4). High temperatures are related to metabolic activity stimulation of both soil microbiota and fauna, thus inducing decomposition of organic matter, while high annual precipitation relates to high net primary productivity (NPP) of plants, and hence to high inputs of organic debris to soil. C inputs are mainly limited by NPP, which depends on climate, and particularly, on the limitations in soil water and nutrients availability (Rabbi et al., 2015). Some studies in semi-arid Australia show that climate and soil properties better explain SOC variability compared with land use and management (Rabbi et al., 2015; Hoyle et al., 2016). Conversely, Fantappie et al. (2011) and recently Schillaci et al. (2017b) show that changes in land use and management seem to have played a major role in the variations of SOC content in Italy and Sicily, respectively.

Some authors (Jobbagy and Jackson, 2000) have pointed out that the importance of soil properties such as clay on SOC stocks increases with soil depth, playing a larger role than climate in deep layers. Given the protective role of clay, a positive impact on SOC stocks at modelling was expected. The results (Fig. A.9) show that such a positive relationship occurs only up to a given limit: about 30 kg/m^2 of clay in the topsoil, and about 125 kg/m^2 in the subsoil. From this limit on, increasing clay abundance does not result in increased SOC stocks. Indeed, a negative trend was detected in the topsoil: with very high clay stocks, SOC stocks tend to decrease. In fact, clay has a dual effect on SOC stocks (Rovira et al., 2010): positive (the protective effect on soil organic matter and the positive effect on soil water holding capacity) and negative (high amounts of clay make penetration by roots difficult, and available water for plants may be low).

Table 4. Summary of relevant information from some of the references cited with regard to modelling SOC, important SOC drivers and agricultural

Region	Land uses	Model	Maximum depth (cm)	R^2	SOC drivers	Cropland SOC stocks ^{a} (kg C/m^2)		References
						0-30 cm	0-100 cm	
Catalonia, NE Spain	Cropland, grassland and unused land	GLS and GWR	100*	0.20-0.35	Climate, soil properties and agricultural management	3.57-6.92	9.20-14.65	*This paper*
Denmark	Forest, cropland, and Wetlands	RK	100*	0.23-0.43	Climate, land use, soil properties, topographic and hydrological indices.		12.1	*Adhikari et al., 2014*
Murcia (SE Spain)	Forest, shrubland and cropland	Stepwise multiple regression analysis	100*	0.11-0.45	Climate, land use, soil properties.		6.3	*Albaladejo et al., 2013*
Western Australia	Cropland	Generalized additive mixed models	30*	0.72-0.79	Climate variables, land use and agricultural management	3.5		*Hoyle et al., 2016*
Jianghan Plain (China)	Forest, cropland, wetland and unused land	OK, MLR, GWR, RK and GWRK	30	0.06-0.31	Topography, spectral indices and distance to road	5.03		*Liu et al., 2015*
Spain	Cropland, grassland and Forest	OK	30	----	Climate and agricultural management	3.81-6.81		*Rodriguez-Martin et al., 2016*
France	Cropland, grassland, forest, schrubland and wetland	BRT	30	0.91	Climate, soil properties and land use	3.2-7.57		*Martin et al., 2011*
Sicily (Italy)	Cropland	SGT	30	0.470	Climate, soil properties, land use and remote sensing information	3.5-4		*Schillaci et al., 2017a*

Model name abbreviation: Ordinary Kriging (OK), Regression kriging (RK), Boosted regression tree (BRT), Multiple Linear Regression (MLR), geographically weighted regression kriging (GWRK), and Stochastic Gradient Treeboost (SGT). *analysis by depth interval.

4.4 Spatial variability of the effect of explanatory variables on SOC Stocks

The results show how at the topsoil the GWR coefficients for the climate variable MAP/MAT presented a negative counterintuitive sign in an agricultural area irrigated since the mid-19th century, the Ebro Valley (Fig. 5a). This negative relationship could be attributed to higher SOC stocks than expected in an area characterized by low precipitation and high temperatures. Possibly the impact of irrigation on the area could mask climatic effects. Rainfed coefficients were negatively stronger (Fig. 5b) at the topsoil, but only in those areas where aridity (Fig. A.1, d) is more pronounced, indicating a stronger positive relationship between irrigation and SOC stocks in these semi-arid areas. Agricultural land use coefficients were negatively stronger in the middle region of Catalonia for all cropland types (Fig. 5c and Fig. A.6 from b to g), demonstrating that in this area alone SOC stocks present lower values regardless of the cropland category. The effect of each factor on SOC stocks at top and subsoil between regions was different (Fig. 5 and Fig. A.3 and A.5). Spatial variability of GWR coefficients showed how main drivers in certain locations have lesser impact, leading to a loss of importance with respect to others. This implies that when regional mitigation strategies are formulated, account should be taken of the different impact of drivers at the local scale.

4.5 Mapping: a new baseline

SOC stocks were modelled and predicted assuming a steady state during the sampling period, in order that this map may be used as a baseline in the assessment of possible future spatio-temporal scenarios. Previous studies have succeeded in mapping SOC stocks at the topsoil over the study area. Using a process-based model, Alvaro-Fuentes et al. (2011) mapped SOC stocks in a wider area of NE Spain, showing values relatively far from ours in some land uses such as vineyard, olives or orchards. Notwithstanding all this, similar results have also been shown for annual and woody crops by other studies in Spain using geostatistical analysis (Rodriguez-Martin et al., 2016). The resulting SOC stocks baseline map in the present study offers improvements regarding previous baselines covering the study area. SOC stocks (topsoil) were mapped specifically for agricultural soils in Catalonia based on a high-density sampling data from more than 2000 spatially well-distributed agricultural soil profiles, using a statistical modelling approach and considering the main SOC drivers. Moreover, a higher map resolution for the study area was achieved, compared to existing baselines.

According to Minasny et al. (2017), SOC stocks fluctuate with latitude, insofar as they are greater at higher latitudes and humid tropics and lower in the mid-latitudes. The mean SOC stock value for agriculture in the study area (4.88 kg/m^2) was similar to the values published for countries at similar latitudes.

4.6 Limitations and mapping uncertainties

In addition to the natural variability of SOC stocks, a number of different reasons could explain the low variance shown by models.

Accuracy of data for this purpose is limited. First, stoniness was estimated visually in field sampling and bulk density had to be estimated using expert-derived pedotransfer function from literature. Second, agricultural variables presented information gaps or generalizations that had to be estimated. Third, soil legacy data was sampled from 1980 to 2015, which could challenge the assumption that SOC stocks remained stable over this 35-year period, avoiding any consideration of possible climate change effects during this time. Unfortunately, due to geographical pattern of sampling, it was not possible to test the effect of sampling date on SOC stocks.

Another limitation was the lack of information related to known factors controlling SOC stocks in terms of physical or chemical C protection (Fe and Al oxides, salinity, hydromorphy, pH or clay minerals), or in terms of soil disturbance, soil protection and C inputs, such as current and historical agricultural management practices. Finally, although soil samples are well distributed right across Catalan agriculture, some agricultural areas are poorly represented.

Mapping uncertainties are associated with SOC stock and driver estimations used when modelling. Modelling prediction error and unquantified uncertainties associated with some covariate layers (in some cases, rasterized versions of polygonal mapping) used to map

SOC stocks should also be considered. Residuals' spatial pattern of the GLS model used for mapping SOC stocks at the topsoil (Fig. A.7) evidenced regions presenting under- and over-predictions quite consistently. These regions with higher or lower residuals (under- or over-predictions) need further attention.

4.7 Recommendations and future research

The results of the present study indicate that data quality must be improved to enhance modelling performance and predictions, and to reduce uncertainty in the output map. Future soil sampling efforts should focus on the acquisition of better SOC data, as well as on the collection of as many potential explanatory variables as possible (bulk density, proportion of coarse particles, detailed soil analytics, exact geographical position, detailed land use, past and current agricultural management practices, etc.). Consequently, further work must be done to understand the role of abiotic, biotic and human factors affecting spatial distribution of SOC stocks not considered here, and to build layers representing SOC stock predictors at a reasonably good spatial resolution, especially soil properties.

The resultant outputs of this study would assist in the analysis of different scenarios that help to formulate targeted climate change mitigation and adaptation policies under Mediterranean conditions. In fact, this study sets the baseline for studies exploring future climate change and land use or agriculture management scenarios, such as those published by Yigini and Panagos (2016), Lugato et al. (2014b) or Zhang et al. (2016).

5. Conclusions

The present study found the most important drivers of SOC stocks to be texture, climate and agricultural land use in the topsoil, and soil properties in the subsoil layer, findings that are consistent with previous studies. Topsoil offers management opportunities for C sequestration, since SOC stocks in this soil layer are mainly affected by dynamic variables. The fact that the effect of controlling factors on SOC stocks vary spatially implies that mitigation strategies should be adjusted at the local scale. Based on the available data, a modelled baseline map of SOC stocks in the topsoil (0-30 cm) for Catalan agriculture based on legacy data was produced and provided, improving spatial estimates of regional terrestrial carbon balances. Absolute and mean values of SOC stocks in soils under agriculture in Catalonia down to 30 cm are 47.89 Tg and 4.88 kg/m^2, respectively. This study represents a baseline framework with which to design climate change mitigation and adaptation strategies based on identifying high and low vulnerability areas and on exploring C sequestration potentials of Mediterranean agricultural soils.

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Chapter 4

Modeling impacts of climate change on the water needs and growing cycle of crops in three Mediterranean basins.

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Abstract

In this study, the suitability of major crops currently growing in three case study basins in Catalonia (NE Spain) was assessed for the first half of the 21st century. For this purpose, an estimation was made of net hydric needs (NHN) and a set of agroclimatic parameters. Climate change impacts were estimated at sub-basin level using temperature and precipitation temporal series based on the Third Report on Climate Change in Catalonia under the RCP 4.5 scenario. Potential crop evapotranspiration (ETc, FAO procedure) and monthly water balance considering soil water holding capacity were used to estimate actual evapotranspiration (ETa) and NHN. Over the period studied, NHN would generally rise , with small (+0.1%) to high (+6.6%) increases in the 2020s and moderate (+3.9%) to high (+6.7%) increases in the 2040s. Dynamics would be different for the three basins and general trends vary from crop to crop. At all events, a generalized increase in NHN together with lower water availability could severely limit crop productivity in the case of both rainfed and irrigated crops (irrigation restrictions). Phenological changes could represent a greater constraint for crop productivity. Overall, the number of frost days will decrease (from -0.1 days in March to -8.7 days in April) in the three basins, while extremely hot days will increase (from +0.3 days in July to +3.8 days in August). Growth cycles will begin earlier (from -1 days to -12 days for crops with a base temperature of 10 ºC), and for some crops they will be shorter (from -8 days to -27 days in the case of maize and up to -10 days in the case of vines). The impacts of climate change in the three basins could result in significant limitations for crops if adaptive strategies beyond irrigation and growing cycle issues are not applied. The results of this study could serve as a basis for the development of adaptation strategies to improve and maintain agriculture in the case study basins and in similar regions.

Highlights

- The main impacts of climate change on crops until 2050 was assessed in three Mediterranean basins.
- Modeling was performed at sub-basin level under the RCP 4.5 scenario.
- Net hydric needs of crops are expected to increase (from +0.1% to +6.7%) in all basins.
- Advancement (1-12 days) and shortening (8-27 days) of the growing cycle are expected.
- A baseline to design adaptation and mitigation strategies was drawn.

Keywords

Watershed; Agriculture;
Net hydric needs;
Crop phenology;
Adaptation

1. Introduction

In future climate change (CC) scenarios, the Mediterranean region stands out as a “hot spot” due to projections of substantial increases in temperature and decreases in rainfall (IPCC, 2014), which would lead to marked decreases in water availability throughout the Mediterranean region (Pascual et al., 2015). For example, in Catalonia (NE Spain) average annual precipitation would decrease by approximately 9% and temperature would increase by +1.4 ºC until 2050 (TICCC, 2016). Agriculture is and will continue to be one of the systems most affected by CC, since –alongside radiation– temperature and water are the main drivers of crop production (Phogat et al., 2018; Ruiz-Ramos et al., 2018). In the Mediterranean region, agriculture is expected to be heavily impacted by higher and extreme temperatures, droughts or soil salinity. To be specific, the principal CC impacts on crops would be changes in phenology and growing cycle (Trnka et al., 2011; Caubel et al., 2015; Funes et al., 2016); higher water demands (Savé et al., 2012; Girard et al., 2015; Phogat et al., 2018; Saadi et al., 2015; Valverde et al., 2015; Zhao et al., 2015) and water scarcity (Vicente-Serrano et al., 2017a,b); decreasing yields (Olesen and Bindi, 2002; Saadi et al., 2015; Zhao et al., 2015; Ruiz-Ramos et al., 2018); or soil salinity constraints (Connor et al., 2012; Phogat et al. 2018). Consequently, food production and security would be seriously compromised (Cramer et al., 2018).

Assessing how climate is expected to affect crops is extremely useful for policy makers, planners, farmers and other stakeholders, who can propose and execute adaptation and mitigation strategies at the local/regional scale to make agriculture more resilient to changes (Caubel et al., 2015). The use of combined adaptation measures tailored to site-specific conditions reduces the impacts of CC more effectively than single and generalized adaptation measures: this has been shown by Ruiz-Ramos et al. (2018) for the Mediterranean context, but can probably be applied to other regions. In general, both adaptation and mitigation strategies have to be addressed in order to reduce greenhouse gas emissions (GHGs), sequester carbon, protect crops from extreme events and ensure sustainable use of soil and water (Prestele et al., 2018). Indeed, climate-smart agriculture (FAO, 2013) has been proposed by FAO as a strategy to adapt and build resilience to CC and to reduce agricultural GHGs, while maintaining high yields and ensuring food security. In summary, strategies and policies must consider productivity, adaptation and mitigation as the three interlinked pillars that support the successful achievement of targeted goals for agriculture and CC issues (FAO, 2013). Therefore, when seeking to identify better strategies to make agriculture more resilient, the first step is to assess the main impacts of CC on crops.

Future water availability and water demands call the current water management model into question, so adaptation decisions must necessarily be aimed at improving water management at a policy level (Iglesias and Garrote, 2015) and target both hazards and vulnerabilities, i.e. water supply and water demand issues (Ronco et al., 2017). Changes in crop distribution and crop choices (Valverde et al., 2015), restricting areas of higher water-consuming crops or creating new varieties adapted to CC (Mo et al., 2017), adapting the cropping calendar (Ronco et al., 2017) and crop diversification (Lin, 2011) have all been proposed as strategies of adaptation to CC for the purpose of maintaining crop production. But they should also be considered as part of a water management strategy: restricting the area of high-consuming crops, even if they are not irrigated, will free water resources at the basin level; changing crop distributions according to changes in phenological constraints, reducing the crop cycle and using new varieties with lower water needs would be steps in the same direction.

This study forms part of the LIFE MEDACC Project (LIFE12 ENV/ES/000536 Demonstration and validation of innovative methodology for regional climate change adaptation in the Mediterranean area). One of the main objectives of this project is assessment of the impacts of climate on agriculture, forest and water at the basin level. Ecohydrology served as a central tool, as it allows consideration of human interference on water balance at the landscape level by using the river basin as a geo-hydrological unit (Savé et al., 2012). The basin has been an appropriate natural unit for assessing or planning any initiative or strategy aimed at conservation, regeneration, adaptation or mitigation to CC. Catalonia is suitably representative of the Mediterranean region, since it presents a wide range of climate conditions in a relatively small area (Pascual et al., 2015).

In this study, three basins were chosen to represent the diversity of the Mediterranean at a local scale. They feature a wide range of topographic, climatic and environmental conditions, and land uses of the Mediterranean region, particularly of Catalonia, including inland vs. coastal differences, which makes this study novel. Another novel feature of this study is that this is the first time an improved upscaling of net hydric needs (NHN) has been applied to these three sub-basins. The improved upscaling uses homogeneous climate, crop type and soil type units. This leads to an understanding of how changes in basin water balance result from the combination of changes in crop phenology, potential evapotranspiration and crop distribution in each basin. This approach worked well in previous studies (Savé et al., 2012), showing CC effects such as increased net water needs and changes in phenology and crop growing cycle (Savé et al., 2012), or impacts on apple flowering time (Funes et al., 2016), despite the fact that in those studies AR4 scenarios A1 and B2 were used instead of RCPs of AR5 (IPCC, 2014), a different methodology for projections was employed, results were only obtained for a single coastal basin, and the most notable results corresponded to the second half of the 21st century, a period not considered here.

The main goals of this study were: (i) to estimate annual net hydric needs (NHN) of major crops in the three basins for the baseline period and two future periods under CC conditions, in order to assess agricultural suitability; (ii) to estimate the monthly pattern of NHN of some crops, which helps to explain the different annual NHN responses of crops to CC; (iii) to estimate a set of agroclimatic parameters capable of indicating the consequences of CC for crop phenology and growing cycle, in order to better understand and manage the risks posed by CC; and (iv) to identify a set of possible adaptation solutions, in view of the results obtained.

2. Material and Methods

A general overview of the material and methods is shown in Figure 1.

2.1. Study area

The study area comprises three basins: those of the river Segre, Ter and Muga. The basins are located in Catalonia (NE Spain; Fig. 2) under Mediterranean conditions, with an area of 13,205, 2,952 and 762 km^2 respectively. These basins were chosen to represent the diversity of the Mediterranean region at a local scale, with a wide range of topographic, climatic and environmental conditions (Pyrenean, inland and coastal; Fig. A.1 of Appendix A), and land uses (Table 1).

The Segre is the longest river in Catalonia (it is a tributary of the Ebro River). The Segre basin is highly stressed by agricultural demands (it is the most agricultural and irrigated basin; Table 1). Water demand in the Ter basin is mainly for urban users (74% in 2007) inside and outside the basin, and as a result, the ecological flows defined for the lower part of the river are frequently not achieved. Moreover, the Ter basin is densely forested. The Muga basin is strongly influenced by its coastal condition. Crops obtain 75% of its water, whereas urban users receive 20%.

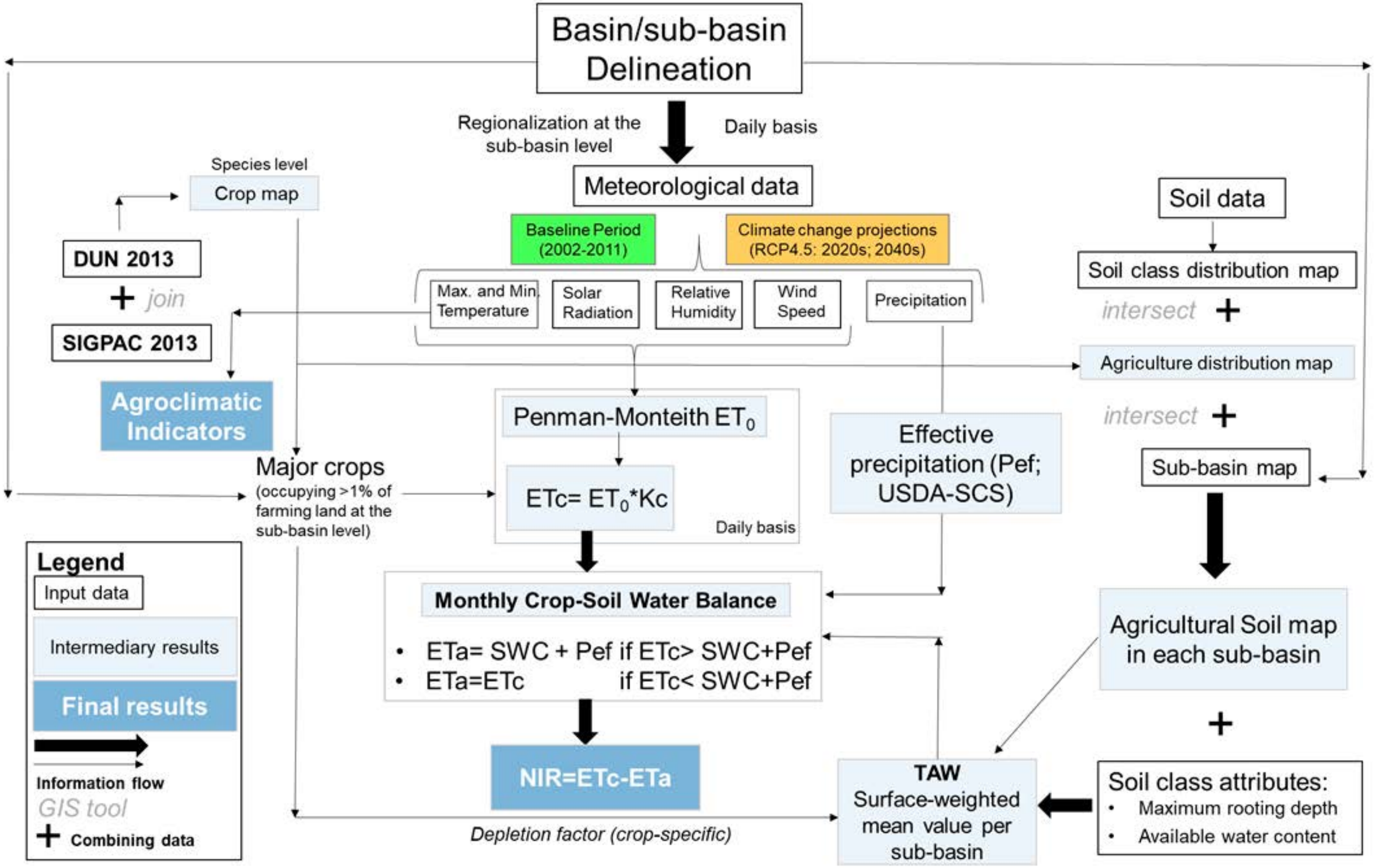

Figure 1. General overview of Material and Methods. ET$_0$ is potential evapotranspiration, ETc is crop evapotranspiration, Kc is crop coefficient, ETa is actual evapotranspiration, SWC is soil water content, Pef is effective precipitation, TAW is total available water and NHN is net hydric needs

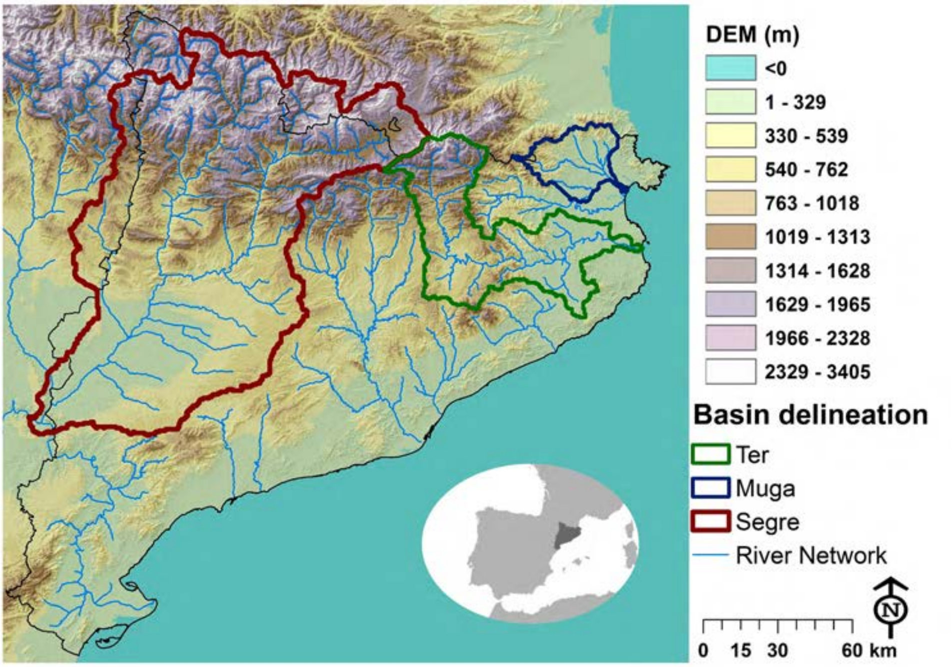

Figure 2. Location of the case study basins. The digital elevation model (DEM) represents altitude (above sea level) in the study area.

Table 1. Areas of major crops and other land uses within the case study basins delineated by SWAT, and percentage of irrigated land for each crop according to the agricultural plots geographical information system (SIGPAC, 2013), the declaration of eligible agricultural area for Common Agricultural Policy payments of the Government of Catalonia (DUN, 2013), and other data sources outside Catalonia (Aragon, France and Andorra). Numbers in brackets are percentages of each land use with respect to the whole basin area.

Land use		**Area (ha)**			**% irrigated**		
		Segre	Ter	Muga	Segre	Ter	Muga
Crops	Winter cereals	185,306	27,011	7,730	16	16	24
	Maize	32,112	5,463	1,912	98	62	90
	Forage crops	40,327	13,437	3,344	66	12	26
	Other Arable land	10,168	4,618	1768	33	18	30
	Orchards	42,863	1,719	449	96	90	53
	Olives	38,770	237	1,473	11	8	1
	Nuts	16,563	879	40	12	50	31
	Vineyards	3,842	72	895	37	5	4
	Tree Farming	85	1,235	-	92	1	-
	Total Crops	**369,950 (28%)**	**54,671 (19%)**	**17,611 (23%)**	38	22	30
	Forest	**296,337 (22%)**	**112,125 (38%)**	**31,421 (41%)**			
	Grassland	**557,712 (42%)**	**103,710 (35%)**	**21,875 (29%)**			
	Urban	**50,781 (4%)**	**15,040 (5%)**	**4,473 (6%)**			

Major crops are considered to be those occupying more than 1% of the crop area at the sub-basin level. Winter cereals comprise wheat, barley, oats and triticale. The group of forage crops is composed of alfalfa, ryegrass, artificial meadows, polyphytic pastures and other forage crops. Other arable land consists of oleaginous crops, cereals and horticulture. Orchards refer to plantations of sweet fruit trees. Nuts are almonds, walnuts, hazelnuts and pistachio trees. Grassland refers to pastures, woodland pastures and bush pastures (all three SIGPAC land uses). Tree farming refers to poplar plantations.

2.2. Basin delineation, climate change projections and meteorological parameter regionalization at the sub-basin level.

Basin and sub-basin delineation was performed using SWAT (Soil and Water Assessment Tool; Arnold et al., 1998) and based on a digital elevation model of 30 m resolution (ICC, 2012). Sub-basin delimitation was based on elevation, creating units with similar areas (Fig. A.2 of Appendix A).

Daily meteorological data were obtained from 340 stations managed by the Spanish State Meteorological Agency (AEMET) and the Meteorological Service of Catalonia (SMC). Some of the meteorological stations also provided data on radiation, relative humidity and wind speed (see spatial distribution of weather stations in Fig. A.3 of Appendix A. The stations were chosen according to their locations within or close to the case study basins, considering climatic heterogeneity and continuity in data series. Climate data were subjected to a process of quality control, filling gaps and homogenization. More detailed information about climate data processing can be found in Appendix B.

CC projections for temperature and precipitation were conducted using the RCP 4.5 scenario (IPCC, 2014) until the time horizon 2050. The RCP 4.5 scenario is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level (Pascual et al., 2016). The time horizon of 2050 was chosen, because short temporal periods are more appropriate for territorial policies in the study area (land planning, irrigation plans, etc.). This may make it difficult to see clear changes from the baseline, but on the other hand the capacity of long temporal time frames to predict reliable changes is limited.

The future temporal series are based on information in the Third Report on Climate Change in Catalonia (TICCC) about the regional dynamic downscaling of CORDEX/EUROCORDEX climate change projections for the three main climatic sub-regions in Catalonia: Pyrenees, Inland and Coast (TICCC, 2016). The changes in temperature and precipitation proposed in TICCC (TICCC, 2016) were applied to the observed temperature and precipitation series of the meteorological stations (those in or near the case study basins) for the baseline period (2002-2011), year by year, at the daily scale, by using the delta method (Zahn and Storch, 2010). A different delta was applied to each month of the year, in accordance with the results of TICCC (2016).

To estimate potential evapotranspiration (ET_0) according to Penman-Monteith, meteorological parameters needed (such as solar radiation, humidity and wind speed) were estimated at a daily scale by using the weather generator included in SWAT (Neitsch et al., 2005). This uses statistics, based on measured records of each weather station, to complete missing information or simulate representative daily climatic data for the sub-basin. More details of these statistics are explained in Neitsch et al. (2011).

Moreover, SWAT was employed to regionalize the meteorological parameter series at the sub-basin scale to be used in the remainder modeling. More details about meteorological parameter regionalization at the sub-basin level can be found in Appendix B.

Taking into account the changes presented in TICCC, the plausible scenario for the study area is a general warming (Table 2 and Fig. A.4 of Appendix A in all the basin segments and in both temporal horizons analyzed (from +0.6 ºC to +1.3 ºC), leading to a general increase in ET_0 (from +2.0% to +4.7%). Projections show higher warming in the sub-regions Pyrenees and Inland than in Coast. As for precipitation, a decrease is likely (between -3.7% and -14.2%; Table 2 and Fig. A.4 of Appendix A), but with lower certainty (TICCC, 2016).

Table 2. Overview of the spatial distribution at the sub-basin level of: a) mean annual precipitation (MAP; mm); b) mean annual evapotranspiration (ET_0; mm) and c) mean annual temperature (MAT; °C) in the three case study basin segments for the baseline period (2002-2011) and differences in % (MAP and ET_0) or °C (MAT) for both future decades analyzed under the RCP 4.5 scenario: 2020s (2021-2030) and 2040s (2041-2050).

		Segre			Ter			Muga		
	Basin Segment	Baseline (mm)	2020s (Δ %)	2040s (Δ %)	Baseline (mm)	2020s (Δ %)	2040s (Δ %)	Baseline (mm)	2020s (Δ %)	2040s (Δ %)
MAP	Upper	**932**	+0.1	-1.4	**981**	-7.5	-8.9	**1,045**	-3.7	-10.0
	Middle	**755**	-14.1	-14.2	**876**	-8.5	-11.3	**811**	-5.7	-11.7
	Lower	**403**	-9.3	-10.1	**760**	-8.7	-12.8	**674**	-7.1	-12.2
ET_0	Upper	**419**	+2.6	+3.5	**805**	+2.7	+4.5	**816**	+2.5	+3.8
	Middle	**907**	+3.7	+4.7	**892**	+2.0	+3.7	**853**	+2.3	+3.3
	Lower	**979**	+3.4	+4.4	**928**	+1.5	+3.1	**870**	+2.1	+3.1
		Baseline (ºC)	2020s (Δ ºC)	2040s (Δ ºC)	Baseline (ºC)	2020s (Δ ºC)	2040s (Δ ºC)	Baseline (ºC)	2020s (Δ ºC)	2040s (Δ ºC)
MAT	Upper	**7.3**	+0.7	+1.2	**9.7**	+0.9	+1.3	**12.6**	+0.60	+1.1
	Middle	**11.8**	+0.7	+1.2	**13.1**	+0.7	+1.1	**14.7**	+0.60	+1.0
	Lower	**14.4**	+0.8	+1.2	**14.7**	+0.6	+1.0	**15.4**	+0.66	+1.0

2.3. Agricultural land uses

A crop distribution map at species level was created for each basin from SIGPAC and DUN for the year 2013 (map scale 1:5,000). Methodological details about the crop mapping can be found in Appendix B.

Most crops in the Segre basin occupy the lower basin and tend to be grouped according to crop typology. The main crops in this lower basin are rainfed winter cereals (Table 1), located mainly in the eastern part of the lower basin and even extending to the middle basin (Fig. 3). The central part of the lower basin (Lleida Valley) is dominated by maize, fruit orchards and alfalfa. In the western part of the lower basin, the agricultural land is primarily occupied by nectarine or peach trees. There are some important areas of grape production, and olives and almonds are grown in the southern part. The lower and middle parts of the Ter basin are devoted to agriculture (Fig. 3). Two crops dominate the lowest part of the lower Ter: apple and maize, which are in fact the two most irrigated crops in the basin (Table 1).

Herbaceous crops such as winter cereals, sorghum, sunflower, rape, etc. and some woody crops such as hazel occupy the remainder of the lower Ter. In the middle Ter, herbaceous crops such as winter cereals, maize, sorghum, rape and fodder crops predominate. Crops in the Muga basin occupy the middle and lower segments (Fig.3). Maize is commonly found in the lower part, while winter cereals are widespread in the lower and middle basin segments. Fodder and woody crops, such as olives and vines (mostly rainfed; Table 1), dominate the middle part of the basin. The irrigated land in this basin is mainly occupied by maize and alfalfa or fruit orchards, such as apple or peach (Table 1). Winter cereals are mostly rainfed, except wheat in the lower basin, with an irrigated area of as much as 43% (Table 1).

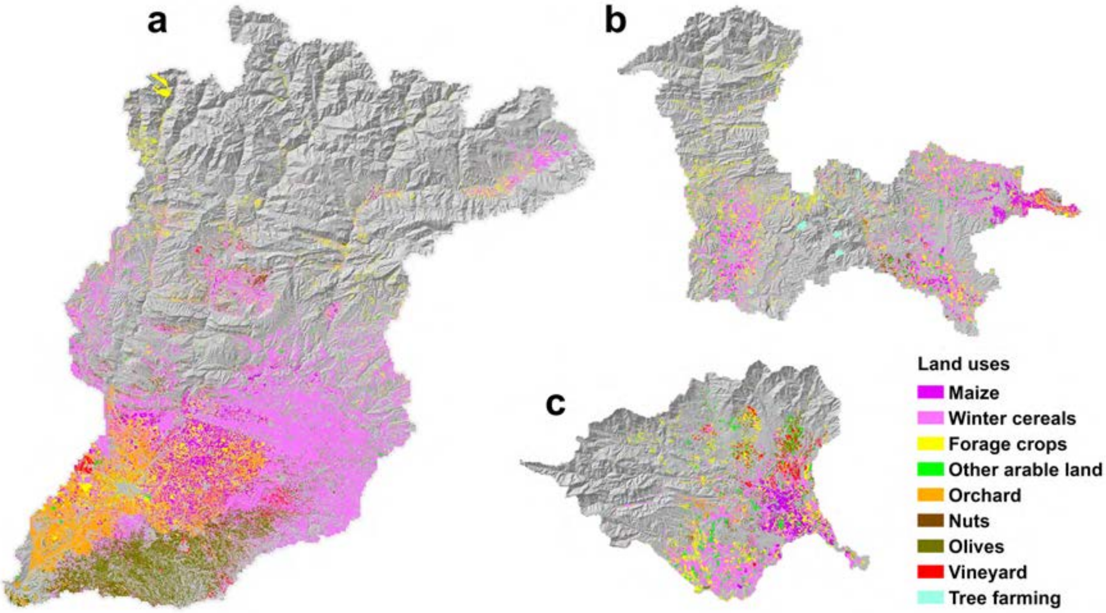

Figure 3. Agricultural land use distribution in the case study basins (a) Segre, b) Ter and c) Muga according to SIGPAC 2013 and DUN 2013 for Catalonia and other regional and national sources for areas beyond Catalonia. A description of land uses in this figure can be found in the footnotes to Table 1. Grayscale hillshading represents topography of non-agricultural areas.

2.4. Available water capacity of agricultural soils

Soil maps were specifically generated for the three basins (map resolution 100x100 m), since they were not previously available for these basins at an appropriate resolution. Details about soil mapping methodology can be found in Appendix B. For each basin, the resulting soil map was intersected with the sub-basin map and the crop map in order to calculate the area of each soil class corresponding to the agricultural land in each sub-basin. In this way, it was possible to estimate an area-weighted mean value in each sub-basin for the following soil attributes: maximum rooting depth of soil profile (Z; mm) and available water capacity of the soil layer (AWC; mm H_2O/mm soil). AWC was calculated by subtracting the fraction of water present at permanent wilting point (the soil water content at a soil matric potential of -1.5 MPa) from that present at field capacity (the soil water content at a soil matric potential of -0.033 MPa) (Neitsch et al., 2011). By multiplying both values (Z and AWC) at sub-basin level, a mean value of a maximum soil water capacity was obtained that could subsequently be used in NHN estimations as the Total Available Soil Water (TAW; mm).

For all three basins, soils were classified into 5 TAW classes (Table 3 and Fig. A.5 in Appendix A). In the Muga basin, cropland mainly corresponds to soils with the two highest TAW classes (ranging from 150 to 300 mm), since the best soils, those with the highest capacity to store water, are sought for agricultural activity. In the Ter basin, crops are grown in the three highest classes of soil (ranging from 100 to 300 mm). However, in the Middle Ter the soils used for agriculture have a lower TAW classification (100-150 mm). In the Segre basin, agricultural land is largely situated in the lower Segre, irrespective of the capacity of soils to store water.Crops with higher water requirements such as maize, alfalfa and fruit orchards occupy the soils with the highest TAW values (200-300 mm), leaving the soils with lower TAW values (<150 mm) to crops such as winter cereals and woody crops such as olives or almonds.

Table 3. Areas (ha) of the total available soil water (TAW) classes in the whole basin and segments of the Segre, Ter and Muga basins. The numbers in brackets are percentages representing the proportion of the total agricultural area occupied by each class.

TAW (mm)	ha (%)											
	Segre				Ter				Muga			
	Total Basin	Upper	Middle	Lower	Total Basin	Upper	Middle	Lower	Total Basin	Upper	Middle	Lower
15-30	**96,663 (24.5)**	2,365 (11.4)	16,636 (19.0)	77,662 (27.1)	**2,081 (3.8)**	329 (8.5)	651 (3.2)	1,102 (3.7)	**189 (1.3)**	19 (10.4)	49 (0.9)	120 (1.3)
30-100	**136,245 (34.5)**	1,771 (8.5)	38,509 (44.0)	95,965 (33.5)	**6,107 (11.3)**	1,389 (35.9)	4,071 (19.8)	647 (2.2)	**1,688 (11.2)**	126 (68.3)	654 (11.9)	907 (9.7)
100-150	**47,306 (12.0)**	10,580 (51.0)	18,297 (20.9)	18,429 (6.4)	**22,889 (42.2)**	1,685 (43.6)	13,400 (65.3)	7,805 (26.1)	**1,654 (11.0)**	30 (16.1)	1,281 (23.3)	344 (3.7)
150-200	**13,888 (3.5)**	97 (0.5)	1,716 (2.0)	12,076 (4.2)	**9,985 (18.4)**	39 (1.0)	783 (3.8)	9,163 (30.6)	**8,400 (56.0)**	3 (1.6)	2,332 (42.4)	6,065 (65.1)
200-300	**101,044 (25.6)**	5,950 (28.7)	12,338 (14.1)	82,756 (28.8)	**13,220 (24.4)**	426 (11.0)	1,615 (7.9)	11,179 (37.4)	**3,075 (20.5)**	7 (3.7)	1,186 (21.6)	1,882 (20.2)

2.5. Net hydric needs estimations

Daily crop potential evapotranspiration (ETc, mm day-1) was calculated for major crops (those occupying more than 1% of the crop area at sub-basin level) in the three basins according to FAO procedure in Allen et al. (1998). ET_0 was calculated from the meteorological series regionalized at the sub-basin level by SWAT from 2002 to 2050. First, daily potential evapotranspiration (ET_0, mm day-1) was calculated in the usual way by applying the Penman-Monteith equation, which is the most appropriate for a Mediterranean climate of all the methods available in SWAT for potential evapotranspiration estimation (Licciardello et al., 2011). Secondly, ETc was calculated for each major crop in each sub-basin from the general ET_0 of the sub-basin and a crop coefficient (Kc, dimensionless) modified by crop phenological stage, as follows:

$$ETc = ET_0 . Kc \qquad \text{Eq. 1}$$

Since the reference surface considered for ET_0 is a hypothetical grass reference crop that resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground (Allen et al., 1998), ETc of grassland and other herbaceous crops such as ryegrass were considered to be equal to ET_0 (Kc=1). In the case of alfalfa and olives, ETc was estimated using a fixed Kc value of 0.78 and 0.65, respectively. For the remaining major crops, Kc values were based on those published in ACA and IRTA (2008), a compilation of different studies estimating Kc coefficients for different crops in Catalonia (Girona et al., 2004, 2011, Marsal et al., 2013, 2016). Kc coefficients are defined in these publications following the crop growth function, based on accumulated growing degree days (GDD). For this study, GDD were adapted to different base temperatures depending on the crop typology. More details are described in Vicente-Serrano et al. (2014).

Under FAO procedure, ETc corresponds to the crop evapotranspiration under standard conditions. These standard conditions refer to crops grown in large fields under excellent agronomic and soil water conditions. However, ETc may actually be limited by available water coming from rain and soil water content. In this case, ETc is reduced to the so-called actual evapotranspiration (ETa, mm month-1). Thus, for the land area occupied by each crop in each sub-basin, a monthly water balance was recurrently calculated to obtain ETa from ETc, effective precipitation (Pef, mm month-1) and the soil water content (SWC, mm month-1), as follows:

$$\text{if } ETc > SWC_{-1} + Pef; \quad \begin{cases} ETa = SWC_{-1} + Pef & \textbf{Eq. 2} \\ \text{and} & \\ SWC_C = 0 & \textbf{Eq. 3} \end{cases}$$

$$\text{if } ETc < SWC_{-1} + Pef; \quad \begin{cases} ETa = ETc & \textbf{Eq. 4} \\ \text{and} & \\ SWC_C = SWC_{-1} + Pef - ETa \text{ or } SWC_C = RAW & \textbf{Eq.5} \end{cases}$$

where ETc, ETa and Pef are from the current month, SWC_{-1} is the surplus SWC at the end of the previous month and SWC_C is water remaining in the soil at the end of the current month and available for crop consumption in the water balance of the next month (i.e. SWC_C of current month equals SWC_{-1} of next month, and so on). RAW (readily available water, mm) is the amount of water that a crop can extract from the root zone without suffering water stress. RAW was calculated for each crop and sub-basin from Total Available Water for each basin (TAW, see section 2.4) and a depletion factor (p) for each crop:

$$RAW = p \cdot TAW \qquad \textbf{Eq. 6}$$

Theoretically, p ranges from 0 to 1. A value of 0.50 for p is commonly used for many crops. For major crops in the case study basins, values for p in the range of 0.50-0.55 were quite common. The minimum value for p was 0.40, corresponding to almonds, and the maximum 0.65, corresponding to olives (Allen et al., 1998).
Hence, after RAW calculation, SWC surplus for the next month (SWC_C) is calculated as:

$$SWC_C = RAW \qquad \text{if } SWC_{-1} + Pef - ETa > RAW \qquad \textbf{Eq. 7}$$

$$SWC_C = SWC + Pef - ETa \qquad \text{if } SWC_{-1} + Pef - ETa < RAW \qquad \textbf{Eq. 8}$$

Pef in equations [2], [5], [7] and [8] was calculated according to Clarke (1998):

$$Pef \begin{cases} Pef = \dfrac{Pt(125 - 0.2Pt)}{125};\ (Pt < 250\text{ mm}) & \textbf{Eq. 9} \\ \\ Pef = 125 + 0.1Pt;\ (Pt \geq 250\text{ mm}) & \textbf{Eq. 10} \end{cases}$$

where Pt is the total monthly precipitation (mm).
Finally, net hydric needs of the crops (NHN, mm month^{-1}) at the monthly scale were calculated as the difference between ETc and ETa:

$$NHN = ETc - ETa \quad \text{Eq. 11}$$

Calculated in this way, NHN does not take account of water inefficiencies in the irrigation system or water pipes used for distribution, i.e. only plant level water requirements are considered. Moreover, projections of NHN estimations in this study do not take into consideration possible changes in agricultural land use (crop changes, abandonment, afforestation, or conversion to urban or industrial soil) for the first half of the 21st century. Theoretical net hydric needs of major crops were calculated for both rainfed and irrigated cropland in each basin.

2.6. Phenological and agroclimatic indicators

Phenological and agroclimatic indicators were calculated to assess the suitability of present-day crops to conditions projected for the near future. A set of general agroclimatic indicators was calculated for the baseline period and the future period up to 2050 under the RCP 4.5 CC scenario. Indicators affecting crops in general were estimated following Savé et al. (2012) and are detailed in Table 4. In addition, some crop-specific indicators for maize, grapevine and apple were calculated.

Table 4. General and crop-specific phenological and agroclimatic indicators of climate change impacts on agriculture: definition, units, climatic parameter on which each indicator is based, and basin segment in which they were estimated. Tmax is the daily maximum temperature (ºC), Tmin is the daily minimum temperature (ºC), Tmean is the daily average temperature (ºC) and DOY is the day of year.

Crop	Climate impacts	Phenologic/ Agroclimatic indicator	Definition	Units	Climatic parameter	Basin Segment
All major crops	Frost damage in germination of some cereals and flowering woody crops	*Frost days*	Number of days with minimum temperature lower than 0ºC in March and April	days	Tmin	All basins and segments
	Heat damage in blossom and grain formation of some cereals	*Heat 30 days*	Number of days with temperature higher than 30 ºC in July and August	days	Tmax	
	Heat damage/stress in fruits of orchards	*Heat 35 days*	Number of days with temperature higher than 35 ºC in July and August	days	Tmax	
	Beginning of growing cycle of most of the crops	*DOY T10*	Day when daily mean temperature begins to be higher 10ºC	DOY	Tmean	
Maize	Duration of growing cycle	*DOY 600FAO*	Day when 2,076 GDD (Tbase=10ºC) were reached from 1st January to assess the cycle duration of FAO cycle grain maize varieties of 600	days	Tmean	Lower Segre; Lower Ter; and middle and Lower Muga
	Duration of growing cycle	*DOY 700FAO*	Day when 2,126 GDD (Tbase=10ºC) were reached from 1st January to assess the cycle duration of FAO cycle grain maize varieties of 700	days	Tmean	
Grapevine	Time and duration of phenologic stages	*DOY pheno*	Date when grapevine budbreak, flowering, fruitset, pea size, veraison and harvest stages are completed[a]	DOY	Tmean	Lower Segre
		Days pheno	Days passing between phenological stages[a]	days		
Apple	Time of phenological stages	*DOY bloom*	Date when apple flowering is completed in 8 apple cultivars[b]	DOY	Tmax and Tmin	Lower Ter

[a] Time and duration of phenological stages of grapevine were estimated based on phenology records from South Catalonia (data not [a] Time and duration of phenological stages of grapevine were estimated based on phenology records from South Catalonia (data not shown) and calculating accumulated a mean value of GDD needed to reach each stage at Tbase=10 °C (Budbreak: 71 GDD; Bloom: 319 GDD; Fruitset: 429 GDD; Berry at pea size: 429 GDD; Veraison: 221 GDD; Harvest: 1,857 GDD; Leaf Fall: 2,163 GDD).

[b] DOY bloom for apples was estimated according to Funes et al. (2016)

3. Results

Results were analyzed for the baseline period (2002-2011) and for two time horizons for the RCP 4.5 scenario (2020s, from 2021 to 2030, and 2040s, from 2041 to 2050). They were aggregated at three segments in each basin (upper, middle and lower basin segments; see Fig. A.2 of Appendix A).

3.1. Climate change impacts on net hydric needs of crops

3.1.1. Current and future annual crop NHN: spatial distribution

Spatial distribution of the estimated current and future annual crop NHN in the three basins is presented in Figure 4. The highest current NHN (more than 3,000 m^3/ha) are concentrated in the lower Segre (Fig. 4a) associated with maize and forage crops (from 4,500-5,000 m^3/ha) and orchards (from 3,000 to 4,500 m^3/ha). In the Ter and Muga basins, higher current NHN are located in lower basin segments, mainly represented by maize, forage crops and orchards, ranging from 2,000 to 4,000 m^3/ha (Fig. 4b and c). In the middle and upper Muga, crops –predominantly winter cereals and olives– present current annual NHN of below 1,000 m^3/ha. Crops in the middle Ter present current annual NHN of 500 to 1,500 m^3/ha.

Most crops in the Segre basin are expected to experience increases in NHN (warm color ramp) with respect to the baseline (Fig. 4a) in the 2020s. These increases will stabilize or slow down in the 2040s, except for the upper course and some areas in the middle and lower basin, where NHN could decrease (cold color ramp), which explains the behavior of the total annual NHN for the whole basin (Table 5). The Ter basin presents the most variable response of crop NHN to CC of the three basins (Fig. 4b). Annual NHN could increase for most major crops in both future periods with respect to the baseline and right across the basin (warm color palette). The general trend is an increase in absolute values for the whole basin (see Table 5), except for some areas of winter cereals, for which annual NHN could decrease (cold color palette) in both periods in the lower basin, despite some recovery in the 2040s.

Crops in the Muga basin show a slight increase in their NHN (green-yellow color palette) as a response to CC from the baseline period to future periods (Fig. 4c), except for forage crops (sharp increase in NHN) and winter cereals (decrease in NHN). Forage crops show a considerable increase in the 2020s, higher than in the case of other crops (warmest colors), but since the proportion of these crops is relatively small in the Muga basin, their effect on NHN at the whole basin level is negligible; there is a much higher proportion of winter cereals, which show a decrease in NHN in the 2020s (cold colors), and this moderates the increase in all other crops, leading to a slight overall increase for the whole basin in the 2020s (Table 5).

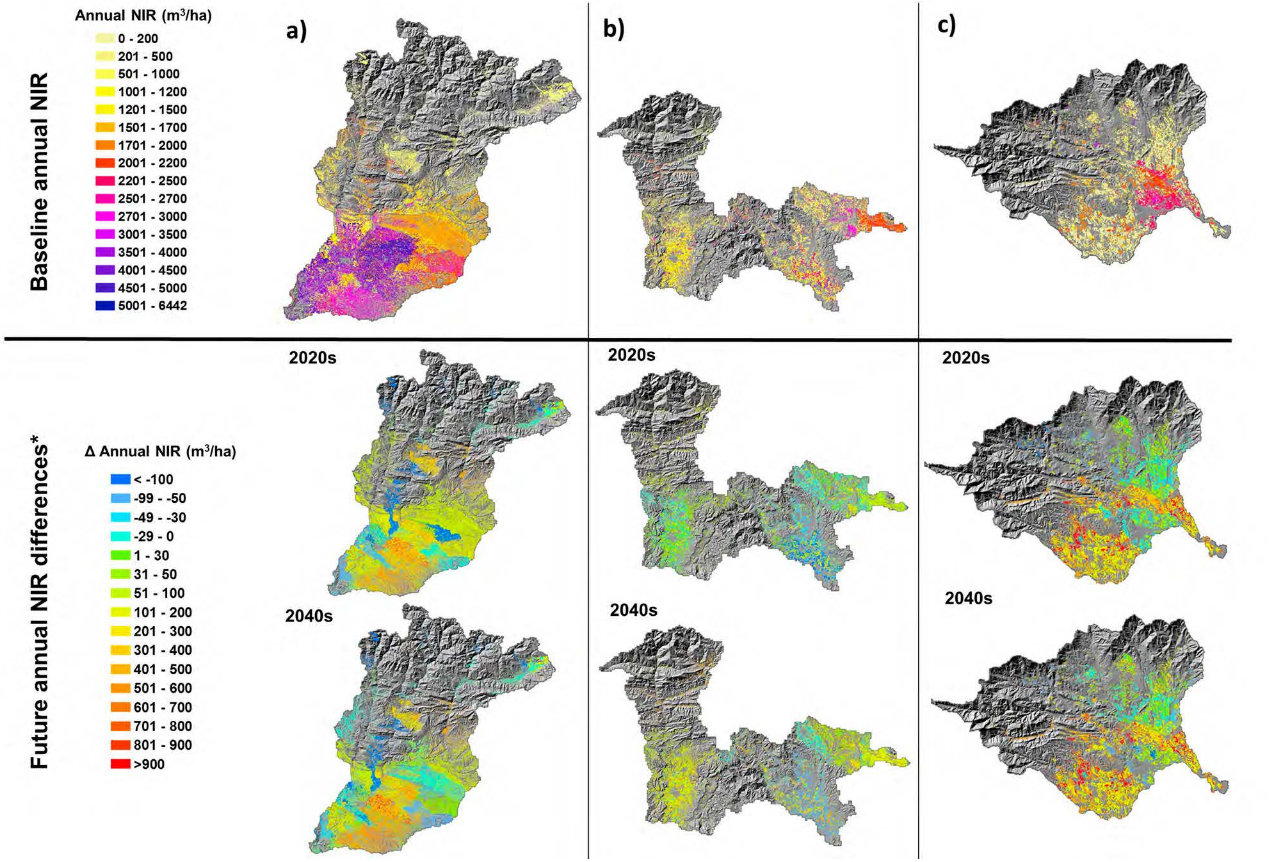

Figure 4. Spatial distribution of the annual net hydric needs (NHN) of major crops in the three case study basins (a) Segre, (b) Ter, (c) Muga in the baseline period (above), and future annual NHN differences from the baseline period at two future time periods: 2020s (2021-2030) and 2040s (2041-2050); *negative annual NHN differences imply decreases and positive differences imply increases with respect to NHN in the baseline period.

3.1.2. Current and future annual crop NHN: total basin values

Total annual NHN values in hm^3 are expected to increase for the Ter and Segre basins, although trends show different patterns in the speed and intensity of change (Table 5). In the Segre basin, the total annual increase in NHN with respect to the baseline would reach almost 53 hm^3 in the 2020s and 54 hm^3 in the 2040s, an increase of 6.6% and 6.7% respectively. In the Ter basin, the increase with respect to the baseline would be almost 1.6 hm^3 in the 2020s and 6.6 hm^3 in the 2040s, an increase of 2.5% and 10.3% respectively.As for the Muga basin, calculations show a total annual increase in NHN of almost 0.02 hm^3 in the 2020s and 0.61 hm^3 in the 2040s (an increase of 0.1% and 3.9% respectively), but these estimates are not statistically significant. In general, the highest increases are observed for the lower and middle basin segments, although higher relative changes (%) appear in some upper basin segments (Table 5). In the lower Segre, mean annual NHN of crops would rise from 2,903 m^3/ha in the baseline to 3,099 m^3/ha in the 2040s. The corresponding figures for the lower and middle Ter from the baseline to the 2040s would show an increase of almost 100 m^3/ha and 150 m^3/ha respectively. Finally, as no variation in land use or crop distribution is assumed between periods, NHN changes calculated between periods by area (m^3/ha) show the same trends and statistical significances as absolute NHN values in hm^3/year; thus, no statistically significant variation in m^3/ha between periods was obtained for the Muga basin.

Total annual NHN values (hm^3) show statistically significant differences between basin segments in all periods, with the lower course always returning the highest figures, and the upper course the lowest. The same pattern may be observed in the mean annual NHN of crops (m^3/ha) when comparing the basin segments of the Segre. However, in the Muga basin, while the upper and middle segments returned similar lower values across the different periods, the lower course showed the highest values. For its part, the Ter basin showed a gradient from the lower to the upper segment, with the middle segment presenting intermediate values not statistically different from the other two segments.

Table 5. Annual average theoretical NHN values for the total basin and lower, middle and upper basin segments (absolute values in hm^3/year and mean values in m^3/ha for the whole basin) for the baseline period (2002-2011) and both future periods under the RCP 4.5 climate change scenario: 2020s (2021-2030) and 2040s (2041-2050). Differences (hm^3) and relative changes (%) in absolute NHN values of major crops with respect to the baseline period. Statistical differences in values between periods are represented with lower case letters and differences between basin segments are represented with upper case letters within each basin. Significant differences in mean values between periods and basin segments were tested by ANOVA ($p<0.05$) within each basin. No interactions were detected.

		Total Basin NHN (hm^3)	**Differences* Δ hm^3 (Δ %)**		**Mean basin NHN (m^3/ha)**		
Basin	**Basin Segment**	**Baseline**	**2020s**	**2040s**	**Baseline**	**2020s**	**2040s**
Segre	Lower basin	695.8	+43.73 (+6.3)	+47.00 (+6.8)	2,903	3,085	3,099
	Middle basin	98.9	+10.19 (+10.3)	+7.96 (+8.1)	690	761	745
	Upper basin	4.98	-1.09 (-21.8)	-1.10 (-22.1)	212	166	165
	Whole basin	**799.7**	**+52.83 (+6.6)**	**+53.85 (+6.7)**	**1,967**	**2,097**	**2,099**
Ter	Lower basin	36.2	+0.50 (+1.4)	+2.80 (+7.7)	1,286	1,302	1,384
	Middle basin	24.2	+0.60 (+2.5)	+2.90 (+12.0)	1,219	1,248	1,367
	Upper basin	3.6	+0.50 (+13.9)	+0.80 (+22.2)	979	1,111	1,207
	Whole basin	**64**	**+1.60 (+2.5)**	**+6.60 (+10.3)**	**1,239**	**1,269**	**1,365**
Muga	Lower basin	10.7	-0.04 (-0.4)	+0.20 (+1.9)	1,420	1,414	1,447
	Middle basin	4.6	+0.08 (+1.6)	+0.41 (+9.0)	584	594	637
	Upper basin	0.28	-0.01 (-4.2)	-0.001 (-0.5)	964	923	959
	Whole basin	**15.6**	**+0.02 (+0.1)**	**+0.61 (+3.9)**	**992**	**993**	**1,031**

* Relative change (%) with respect to the baseline period.

3.1.3. Crop-specific current and future mean annual NHN

In the Segre, typical rainfed crops such as grapevine and almond could present an increase in their mean annual NHN in the 2040s from 9 to 15%, with olives showing an increase of up to 17% in the lower basin, where agriculture is concentrated (Table A.1 of Appendix A). In general, winter cereals would report an increase (around 43% for barley) in the 2020s, and a subsequent slowdown in the 2040s, in accordance with the general pattern for this basin. NHN of fruit orchards such as apple would increase by up to 10% in the lower basin in the 2040s. Finally, pastures in the middle Segre would increase by up to 45% in the 2020s and almost 50% in the 2040s.

In the Ter basin, annual mean NHN of maize could increase by up to 9% and 14% in the 2040s in the lower and middle segments respectively (Table A.2 of Appendix A). Annual NHN of ryegrass could increase by up to 11% and 15% in the 2040s in the lower and middle segments respectively, and by almost 22% in the upper segment. Winter cereals follow the same pattern in the middle and upper basin, where NHN could increase by around 10% in the 2040s. However, in the lower basin, annual NHN of winter cereals could decrease by up to 9% in the 2020s and 5% in the 2040s. Finally, in the 2020s and 2040s, annual NHN of apple trees in the lower basin could increase by around 3% and 9% respectively.

In the Muga basin, olives would consistently show an increase in NHN in the lower and middle segments, including an increase of up to 24% in the 2040s in the middle basin, where this crop is widespread (Table A.3 of Appendix A). Grapevines would show an increase of up to 10% in the 2040s. In the same period, forage crops (alfalfa or pastures) in the middle and lower Muga could record increases with respect to the baseline of more than 8% and more than 11% (3000-4000 m^3/ha). Also in the 2040s, winter cereals such as barley could show a decrease of more than 11% and almost 23% in the middle and lower Muga respectively. Maize could see increases of almost 1% and 4% in the 2040s in the lower and middle Muga respectively.

3.1.4. Monthly crop NHN patterns

Some of the annual NHN results, such as the decrease in the annual NHN of winter cereals in several sub-basins, are easier to understand if an analysis is made of monthly behavior patterns in the NHN of crops. In general, an earlier increase in ETa in the year and a subsequent decrease for both future time horizons analyzed is observed, but it is only reflected in an increase in total annual NHN depending on crop phenology, so different monthly NHN patterns can be observed (Fig. 5). For instance, in general, in the case of orchards such as olive trees in the lower Segre, a first monthly NHN pattern can be observed: NHN only increase from May to July (Fig. 5), but no NHN increases were observed in the following summer months for future horizons with respect to the baseline (growth cycle advancement due to increased temperatures) and the annual NHN increase was modest. On the other hand, a second monthly NHN pattern for future horizons was observed in the case of forage crops, such as pastures in the middle Segre (Fig. 5): higher NHN in most of the spring and summer months, resulting in a higher annual NHN increase. Finally, a third monthly NHN pattern for future horizons may be observed in a number of crops and basin segments, such as maize in the lower Ter and barley in the lower Muga (Fig. 5): an increase in NHN in the early growing cycle balanced by lower NHN later in the cycle for phenological reasons (growth cycle advancement due to increased temperatures), resulting on occasions in an annual decrease in NHN with respect to the baseline.

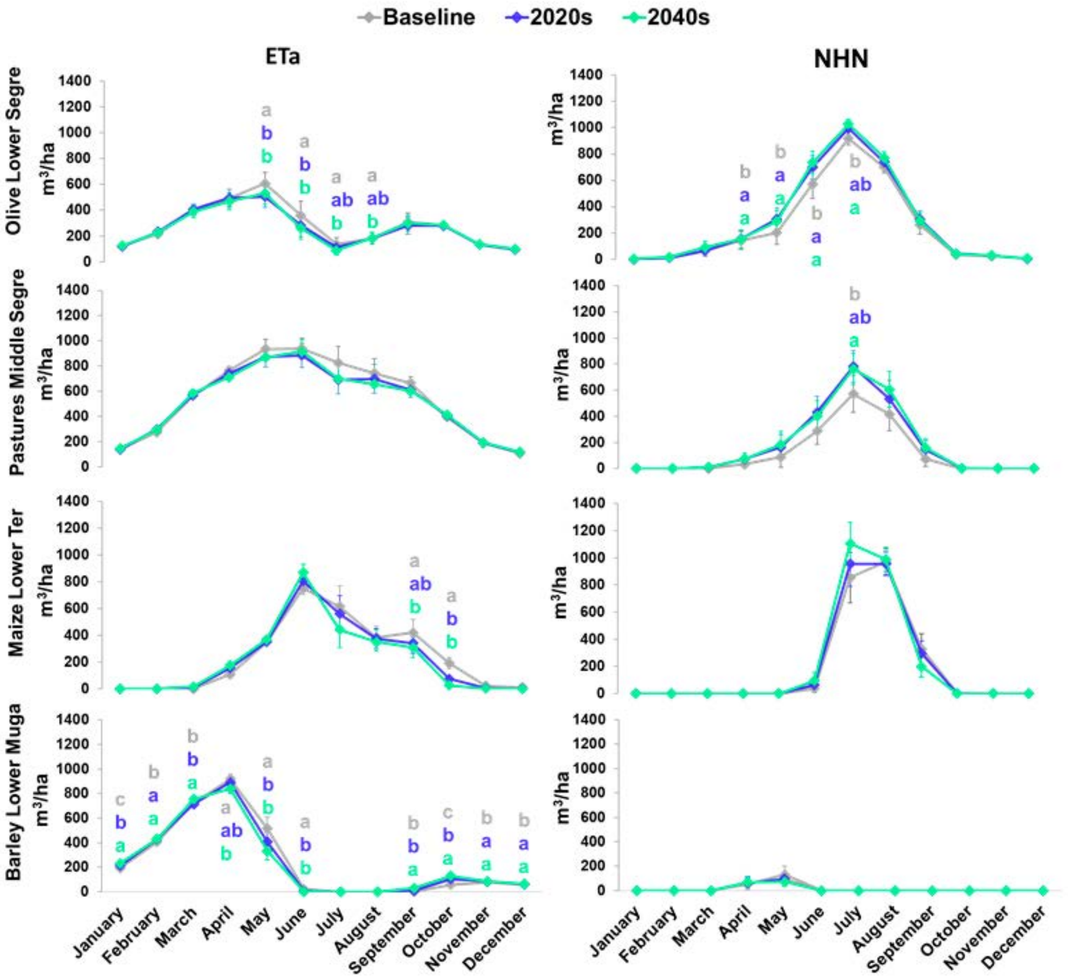

Figure 5. Patterns in monthly actual evapotranspiration (ETa, left) and net hydric needs (NHN, right): from bottom to top, barley in the lower Muga, maize in the lower Ter, pastures in the middle Segre, and olives in the lower Segre in the baseline period (2002-2011), 2020s (2021-2030) and 2040s (2041-2050). Letters represent significant differences between at least two time horizons each months. The color of the letter denotes the time horizon: gray for baseline, blue for 2020s and green for 2040s. Significant differences between mean monthly NHN values were tested by ANOVA ($p<0.05$). Time horizons with the same letter are not significantly different. An absence of letters denotes no significant differences between any time horizon.

3.2. Climate change impacts on crop growing cycle and phenology

The three patterns observed in monthly NHN in the previous section mostly reflect variations in the growing cycle determined from GDD accumulation, which produced a general advancement in the growing cycle and, depending on the species, a shortening of the cycle as well. Apart from GDD accumulation, several general agroclimatic indices calculated show this, but the specific growing cycle indices estimated for several species (maize, grapevine and apple) also show changes in their respective growing cycles.

Frost days in March and April would decrease throughout the three basins, most markedly in the upper and middle basin segments (Table 6). This does not necessarily mean a reduction or disappearance of frost risk because of the advancement of the crop cycle, as can be seen in *DOYT10*, which indicates an advancement of the growing cycle of up to 8-12, 7-10 or 5-8 days in the lower, middle and upper basin, respectively, in the 2040s. The number of days with risk of heat damage in July and August would increase in all basins and segments (Table 6). *Heat 30 days* shows an increase of 3-5 days in the 2040s depending on the basin and the segment, except in the upper Segre where the increase in the 2040s is barely 1 day. *Heat 35 days* would approximately double in all basins in the 2040s in relation to the baseline.

Both maize-specific indicators related to the rapid completion of the growing cycle (*DOY600FAO* and *DOY700FAO*, Table 6) show that it could be shortened in the 2040s compared to the baseline, ranging from 20 to 27 days shorter, depending on the basin and segment. For grapevine, *DOY pheno* at budbreak would be reached 7 days earlier in the 2020s and 10 days earlier in the 2040s compared to the baseline (Fig. A.6 of Appendix A), while *Days pheno* to harvest after budbreak (180 days in the baseline period) would be shortened by up to 6 days in the 2020s and 11 days in the 2040s, mainly due to shortening in all phases after blooming, particularly from veraison to harvest. Although *Days pheno* at the blooming phase would last up to 6 days longer in the 2040s, *DOY pheno* at blooming would be slightly advanced because of earlier budbreak. Finally, the shortening of the growing cycle would result in an earlier DOY pheno at harvest of about 13 days in the 2020s and 21 days in the 2040s. DOY bloom in apples would show no changes in the 2020s or 2040s: in spite of a delay at the beginning of chill accumulation of almost 10 days, an equivalent, counterbalancing effect is observed during the heat accumulation phase, and no changes would occur during the chilling phase (Fig. A.7 of Appendix A).

Table 6. General and maize-specific indicators for growth and development in the upper, middle and lower segments of the case study basins for baseline (2002-2011) and future periods (2020s and 2040s) under the RCP 4.5 scenario. The definition of each indicator can be found in Table 4.

			Segre									Ter									Muga								
			Upper			Middle			Lower			Upper			Middle			Lower			Upper			Middle			Lower		
	Indicator		Baseline	Δ2020s	Δ2040s	Baseline	Δ2020s	Δ2040s	Baseline	Δ2020s	Δ2040s	Baseline	Δ2020s	Δ2040s	Baseline	Δ2020s	Δ2040s	Baseline	Δ2020s	Δ2040s	Baseline	Δ2020s	Δ2040s	Baseline	Δ2020s	Δ2040s	Baseline	Δ2020s	Δ2040s
General indicators	Frost days	March	19.6	-0.5	-1.4	13.3	-0.6	-1.8	5.4	-0.4	-1.5	17.3	-1.3	-2.3	7.8	-0.8	-1.9	6.5	-0.3	-0.9	8.4	-1.1	-2.1	2.7	-0.1	-0.1	1.7	-0.1	-0.4
		April	19.6	-7.8	-8.7	4.6	-0.5	-1.1	0.4	-0.1	-0.2	7.1	-1.1	-1.7	0.8	-0.1	-0.5	0.5	-0.1	-0.3	1	-0.6	-0.3	0	0	0	0	0	0
	Heat 30 days	July	0.7	+0.6	+0.9	13.6	+2.9	+5	22.1	+2.7	+4	4.4	+2.8	+5.0	14.1	+2.8	+4.8	17.6	+1.6	+3.0	9	+2.1	+3.9	12.9	+1.9	+3.9	13.8	+2.7	+3.9
		August	0.7	+0.5	+0.9	11.5	+2.8	+4.8	19.2	+3.1	+4.4	3.5	+2.4	+4.5	10.6	+2.8	+5	15.3	+2	+4	5.5	+1.8	+3.8	11	+2.3	+4.7	11.8	+2.7	+4.6
	Heat 35 days	July	0	0	0	2.4	+1.5	+3.2	5.1	+3.3	+5.6	0	+0.3	+0.4	1.2	+1	+1.9	2.8	+1.2	+2.4	0.4	+0.4	+0.9	0.5	+0.5	+0.9	1.2	+0.4	+1
		August	0	0	0	2.4	+1	+2.5	4.2	+1.9	+3.8	0.3	+0.3	+0.6	1.5	+0.6	+1.5	3.7	+0.7	+1.9	0.5	+0.4	+0.6	1.3	+0.2	+0.7	1	+0.8	+1.5
	DOY T10		150	-2	-5	108	-3	-7	82	-4	-10	131	-4	-8	101	-4	-7	80	-1	-8	107	0	-5	79	-4	-10	70	-7	-12
Maize indicators	DOY 600FAO		†	†	†	‡	‡	‡	282	-13	-22	†	†	†	‡	‡	‡	299	-14	-24	†	†	†	299	-11	-23	284	-14	-23
	DOY 700FAO		†	†	†	‡	‡	‡	285	-11	-20	†	†	†	‡	‡	‡	307	-19	-27	†	†	†	303	-8	-20	289	-13	-22

† Maize is not a major crop in this basin segment, so calculations were not performed.

‡ Calculations were not performed as the required GDD are not attained in all years in most of the sub-basins, at least in the reference period.

4. Discussion

Our estimations showed the main impacts of CC on the NHN, growing cycle and phenology of major crops in three Mediterranean basins in the first half of the 21st century under the RCP 4.5 scenario, a GHGs emission stabilization scenario that assumes the execution of mitigation policies (Thomson et al., 2011).

4.1. Projected changes in the NHN of crops

Most crops in the three basins could experience a significant increase in NHN until mid-century with respect to the baseline period (Fig. 4; Table A.1 to A.2 of Appendix A and Table 5), as shown by similar studies under Mediterranean (Phogat et al., 2018; Zhao et al., 2015; Valverde et al., 2015; Savé et al., 2012; see review in Iglesias and Garrote, 2015) and non-Mediterranean conditions (Hong et al., 2016; see review in Iglesias and Garrote, 2015; McDonald and Girvetz, 2013). However, NHN decreases have been calculated for some crops (especially for winter cereals) at certain locations in all the case study basins up until 2050 under the RCP 4.5 scenario. Although NHN decreases are also projected in other studies (Hong et al., 2016; Zhao et al., 2015; Lorite et al., 2018), this is not an obvious result. These decreases are associated with changes in duration (shortening) or beginning (advancement) of the growing cycle, particularly in annual crops (Fig. A.6 of Appendix A). Shortening and advancement of the growing cycle partially compensates or overcompensates the earlier NHN increase in some annual crops. A shortened and advanced growing cycle leads to a lower demand for water due to higher soil water availability, and there is also less time for water to be consumed. We believe there are two main reasons for these novel results: first, they were obtained under the RCP 4.5 scenario, a pathway for stabilization of radiative forcing by 2100 (IPCC, 2014) in contrast with the A2 scenario from AR4; and secondly, we were able to fine-tune our calculations by using homogeneous climate, crop type and soil type units, which leads to more reliable estimations of ETa. The reason we were able to arrive at these fine-tuned results is that our study is one of the few that considers general and exhaustively projected changes in the NHN of major crops at a basin scale, including the range of conditions of a specific region.

In general and in terms of absolute values, NHN would increase in the Ter and Segre basins, albeit in a different way, throughout the first half of the century. NHN increases range from small to moderate in the 2020s to moderate to high in the 2040s. Dynamics would vary for the three basins: there would be no statistically significant variation for the Muga basin a continuous increase for the Ter basin, and an initial increase followed by stability in the Segre basin (Table 5). These general trends vary from crop to crop (Table A.1 to A.3 of Appendix A). The highest increases in NHN are found in the lower segments of the basins, where agriculture is spatially concentrated (Table 5). Most notably, in the lower Segre annual NHN (total values) would increase by 43.7 and 47 hm^3/year in the 2020s and 2040s, respectively. Lower annual NHN increases (total values) are estimated the lower Ter: 2.8 hm^3/year in the 2040s.

At all events, a generalized increase in NHN is observed in the case study basins; combined with lower water availability, which restricts irrigation, this could become very limiting for crop production.

4.2. Projected changes and impacts on crop growing cycle and phenology

A general advancement of the crop growing cycle has been shown throughout the future time horizons in this study. Moreover, a shortened crop growing cycle has been estimated in annual crops such as maize (Table 6) and temperate fruits such as grapevine (Fig. A.6 of Appendix A). However, a general prolongation of the vegetative season was predicted by some authors (Trnka et al., 2011; Tian et al., 2014), opening new time windows for cropping. The behavior of some herbaceous crops such as pastures (Fig. 5) fit this pattern. A higher number of days presenting extremely hot temperature (*Heat 30 days* and *Heat 35 days*) as projected for the three basins (Table 6) is consistent with the current increase in detrimental heat effects in the study area, such as the heat stroke observed in apple (Joaquim Carbó, personal communication), seriously affecting fruit quality.

A decrease in *Frost days* (Table 6) would not necessarily mean a reduction or disappearance of frost risk. In fact, the projected advancement and shortening of the crop growing cycle could counterbalance this reduction in frost days, leading to an increase in spring frost risk (Darbyshire et al., 2013), as early phenological stages may still occur when frost events are still frequent despite the advancement of the crop growing cycle. These changes (Table 6; Fig. A.6 and A.7 of Appendix A) are in line with other studies that assess crop growing cycle and phenology (Trnka et al., 2011; Saadi et al., 2015; Ruiz-Ramos et al., 2018; Koufos et al., 2018).

Upper segments of basins would experience the greatest climatic changes, because they are the coldest and wettest. However, effects on crop production would be higher in the middle and lowest segments of basins since this is where most of the cropland is situated. The coastal effect leads to clear differences between the lower basin and the rest of the basin, except in the case of the Segre, as this is a tributary river and its lower course is clearly inland.

4.3. Adaptation measures and strategies

Adaptation measures and strategies should be consistent with the results presented so far, in order to reduce the future impacts of CC and facilitate the design of more resilient agricultural water management systems in Catalonia as a whole. These measures would mainly consist in: i) changing the water management scheme; ii) changing the crop distribution and crop choices (low water demand crops; Allain et al., 2018; Mo et al., 2017; Ronco et al., 2017); iii) applying support or supplementary irrigation and increasing irrigation efficiency (Ruiz-Ramos et al., 2018; Dechmi and Skhiri, 2013); iv) adjusting irrigation to net irrigation requirements (Dechmi and Skhiri, 2013; Allain et al., 2018; Pascual et al., 2018); v) Adjusting sowing dates and the cropping calendar (Rotter et al., 2013; Ruiz-Ramos et al., 2018); and vi) changing to cultivars or crops more suited to adverse conditions (Mo et al., 2017; Ronco et al., 2017). These measures would also form part of a water management strategy: in line with our results, some research in the study area (Milano et al., 2013 in the Ebro basin and Vicente-Serrano et al., 2017a in the

Segre basin) has concluded that a future scenario characterized by higher demands together with decreased water availability is highly plausible. Therefore, it will be necessary to adopt new water use and management strategies in the case study basins in order to maintain yields and improve agriculture. For example, beyond increasing irrigation efficiency, adjusting irrigation to hydric needs and not to a predetermined concession should form part of a water management strategy in a water and land governance framework; the decision to use low water demand crops or varieties should not simply be left to the growers, but it should also be included in a water governance scheme, together with restricting the area of higher water consuming crops or defining support irrigation protocols to allow crop survival in the driest years.

In fact, many other adaptation measures and strategies could be proposed, such as the following: a shift in diet towards a reduction in meat consumption, since fodder crops are large water and land consumers, (Vanham et al., 2016); changes in land use and forest management to regulate water availability for the basin (Zabalza-Martínez et al., 2018); rainwater harvesting and storage (Rockström, 2002); reuse of wastewater in agriculture (Panagopoulos et al, 2014; Ronco et al., 2017); crop diversification and crop rotation by alternating water-demanding crops with crops that demand less water (Allain et al., 2018; Lin, 2011); and conservation agriculture (Prestele et al., 2018) or physically protecting crops from adverse events by establishing abatement infrastructures. Clearly, some of these measures would also form part of a water management scheme.

As a matter of fact, choosing site-specific measures and combining them are the most appropriate options when seeking to adapt agricultural systems to CC measures (Dechmi and Skhiri, 2013; Ruiz-Ramos et al., 2018). Moreover, the implementation of policies, including water management, with a combination of CC mitigation and adaptation measures is highly recommended in order to make agricultural systems more resilient and obtain high yields (FAO, 2013).

4.4. Limitations of the study

Due to the methodology used in this study for NHN estimations based on Savé et al., (2012), some limitations must be acknowledged that make it necessary to look at our results with some care, although we believe the effect of these limitations is negligible. First, although no uncertainty or validation analyses have been performed, similar annual ETc and NHN values (estimated for the baseline period) were obtained for maize and apple trees in GIROREG experiences (from 2014 to 2017) in the Muga and Ter basins within the framework of LIFE MEDACC (Francesc Camps, personal communication). Similar values of annual NHN for wheat have been reported by Saadi et al., (2015): 275 mm in the area of Lleida compared with 211.6 mm estimated in the present study for the lower Segre (Table A.1 of Appendix A).

Secondly, the delta method used in climate projections will probably not reflect extreme values. However, intra-annual variability is already considered in the projections by using different deltas for the different seasons; and, as projections are applied to mean values for long periods (more than 10 years), interannual variability is not the main focus, also because uncertainty in extreme values is much greater than in mean values.

Thirdly, the effect on crop transpiration of increased CO_2 in the RCP 4.5 scenario was not considered in the NHN calculation. Some authors (Elliot et al., 2014, Zhao et al., 2015) have highlighted the importance of considering increased CO_2. However, following the arguments presented by Savé et al. (2012), we thought that the uncertainties of not considering increased CO_2 effects would motivate a correction of our results, but we do not believe these corrections would raise or lower the estimations presented here. First of all, the CO_2 increase in the RCP 4.5 scenario is very small, so no substancial reductions in stomatal conductance are to be expected, and this reduction would be partially compensated by a higher leaf area index, also resulting from plant adaptation to higher CO_2 concentrations, giving a similar transpiration per soil area.

Fourthly, another source of uncertainty can be found in the use of estimated soil maps for the case study basins, as soil attributes such as available water capacity are determinant for crop NHN estimation through estimation of ETa. However, no complete high-resolution soil maps were available for the study area.

Fifthly, estimations based on phenological and agroclimatic models that are valid in the reference period are implicitly assumed to be valid for the estimated periods. Moreover, the estimated changes in growing cycle in this study are based on GDD accumulation, and changes in phenology for grapevines or maize use very simple models also based on GDD accumulation.

Finally, the health status of the crop would undoubtedly affect these results, and pests and diseases are expected to increase in the Mediterranean as a result of climate change (MedECC, 2019).

Beyond this, crop performance will be affected by agronomical practices, local edaphic conditions and production needs, i.e. the market, which have not been included in the calculations. Moreover, this study has focused on the expected conditions for current crops in the basins where they are now being grown: based on the results in this study, conclusions could be drawn about the degree of productivity of these crops in their present locations.

4.5. Recommendations and future work

Integrating the results of this study with hydrological modeling for future climate and land use scenarios would make it possible to estimate the gap (the deficit or imbalance) between water supply and water demands with regard to agriculture in the area and to design water management strategies.

Moreover, further modeling work becomes necessary for the purpose of simulating different initiatives and/or scenarios (concerning water management, land use changes, best management practices in agriculture and CC scenarios) at the basin or regional scale, in order to test different adaptation and mitigation strategies for Catalonia.

5. Conclusion

Most crops in the case study basins would show significant NHN increases before mid-century, directly related with increased crop potential evapotranspiration and decreased precipitation during the growing season. The generalized NHN increase and the low water availability for irrigation could challenge the feasibility of maintaining the current agricultural model in the study area. Other key results of this work are a general advancement and shortening of the growing cycle, lengthening of the vegetating season, impacts on phenology and damages associated with extreme temperatures. These future scenarios open up new possibilities in terms of crop and variety choices, adjustment of the cropping calendar and a wide range of CC adaptation measures that should form part of any water management scheme within a governance framework. This study represents a starting point from which to simulate adaptation and mitigation strategies that will be instrumental in the design of more resilient agricultural systems in Catalonia, including water management, and its findings could be partially extrapolated to many other regions of the Mediterranean basin.

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Chapter 5

General Discussion and Conclusions

The objective of this thesis was to generate a baseline of approaches in order to explore and test scenarios that support the decisionmaking process when designing Adaptation and Mitigation (ADAM) strategies. The general discussion of this thesis will be focused on four issues: i) the empirical knowledge it has generated as a baseline for enabling ADAM strategies, as well as comparison with other studies and the main limitations of the study; ii) testing future management scenarios for the ADAM decision-making process; iii) exploring a mitigation strategy through a simple approach taken during the thesis period; and iv) future research. Finally, the main conclusionsof this thesis will be listed in the last section of this chapter.

5.1 Empirical baseline knowledge for mitigation and adaptation at the regional scale.

5.1.1 Crop carbon stocks and climate change impacts estimations

The generated results of this thesis were mainly based on a great amount unedited of site-specific, legacy and literature data, data mining, climate projections and regional upscaling. All this knowledge concludes in spatial information at the regional scale that would be helpful in the decision-making process for spatial planning at the landscape level. Therefore, the results offered increased spatial accuracy in carbon (C) stocks estimations at soil and perennial woody structures on the Catalan cropland and climate change (CC) impacts and vulnerabilities. Other inferences could be explained from the thesis results such us the temporal changes of carbon stocks and the relationships with their drivers. Overall, these findings could be partially extrapolated to many other regions of the Mediterranean basin.

The approach to assess carbon stocks in woody biomass of cropland (Chapter 2) could be defined as Tier 2, since region-specific estimates of biomass stocks by major cropland types and manegement systems were considered. The IPCC Tier 1 global estimate for above and belowground biomass of agricultural land was 5 Mg C/ha (Zomer et al., 2016). Our results show that existing woody cropland in Catalonia makes a greater contribution to the carbon pool (16.44 ± 0.18 Mg C/ha) than the IPCC Tier 1 estimation.

Moreover, woody cropland carbon stocks (Chapter 2) were estimated and they increase (0.17 Tg C/year) during the 2010s decade mainly due to growth of trees or vines of the remaining woody cropland. However, these results may suppose the turning point in the trend towards a negative balance in carbon stocks as a direct consequence of the decreased tendency in woody cropland in favor of other uses such as urban and agricultural (mainly grassland and arable land). Conversion of woody cropland to grassland and arable land was partly aimed at feeding the meat industry in the study area, supposing a large consumption of land and water resources and a great source of greenhouse gases (GHGs) emissions (Vanham et al., 2016). Moreover, in Mediterranean basin there is a tendency to decrease woody crops, which are substituted for natural ecological succession, with the normal variability in the transition process due to edaphic, environmental and previous agricultural use (MedECC, 2020). In Mediterranean conditions the main problems generated for crops abandonment are fire due to forest recovering and aridity due to increases in superficial water runoff in arid or semiarid conditions. In this context, the use of woody crops and agronomical practices associated to these (green soil covert, reduction of slopes or terraces development) become important to avoid the above-mentioned problems and maintain agricultural productivity, economic stability, CC mitigation and, in consequence, population and maintenance of landscape. Moreover, woody crops contribute to the maintenance of the mosaic landscape and break forest continuity, helping to avoid big wildfires. Rainfed cereals or abandoned lands could become a problem because of they do not play as well the carbon stock role as woody crops do. The land use change (LUC) observed in the study area would appear to be a direct response to changing market needs, rather than a country strategy focused on food security and ADAM. If no ADAM strategies are considered in territorial management, there will be a trend towards a decrease in woody cropland (mainly rainfed woody crops) and consequently an inevitable decrease in the C pool, together with the loss of a significant element of the Catalonia's landscape, culture and agro-biodiversity.

Chapter 3 modelled agricultural soil organic carbon (SOC) stocks at two soil depth intervals, topsoil (0–30 cm) and subsoil (30–100 cm). The statistical model estimated an average SOC of 4.88 ± 0.89 kg C/m^2 (48.8 ± 8.9 Mg C/ha) at the topsoil. This value is three times higher than the estimated average of carbon stocks on woody cropland biomass (Chapter 2). SOC (topsoil) were also mapped in Catalonia based on a high-density sampling data from more than 2000 spatially well-distributed agricultural soil profiles, using a statistical modelling approach and considering the main SOC drivers. A higher resolution map (pixel size of 180 m) for the study area was achieved, compared to existing baselines and was published in the Cartographic and Geological Institute of Catalonia (ICGC) website where can be downloaded in GIS format.

Moreover, Chapter 3 assessed the importance and effects of different drivers on SOC. The results showed how significance of drivers differed in the top and subsoil and varied spatially at the regional scale, as well. At the topsoil, the main drivers were textural class, agricultural land use and MAP/MAT (Mean Annual Precipitation/ Mean annual Temperature). At the subsoil, the agricultural land use category was still important, but MAP/MAT ratio and water management were no longer significant. Otherwise, the effect of each driver on SOC stocks at top and subsoil was different between regions in the study area. Spatial variability of model coefficients showed how main drivers in certain locations have lesser impact with respect to others. This can have different implications when regional mitigation strategies are formulated, account should be taken of the different impact of drivers at the local scale. For example, the climate variable MAP/MAT presented a negative counterintuitive relationship with topsoil SOC in the central valley of Catalonia, an agricultural area irrigated since the mid-19th century. This negative relationship could be attributed to higher SOC stocks than expected in an area characterized by low precipitation and high temperatures suggesting that the impact of irrigation on the area could mask climatic effects.

The estimations of Chapter 4 showed the main impacts of CC on net hydric needs (NHN), growing cycle and phenology of major crops in three Mediterranean basins in the first half of the 21st century under the RCP 4.5 scenario (a GHGs emission stabilization scenario). At all events, a generalized increase in NHN together with lower water availability could severely limit crop productivity in the case of both rainfed and irrigated crops (irrigation restrictions). Most crops in the three basins could experience a significant increase in NHN until mid-century with respect to the baseline period. In general, and in terms of absolute values, NHN would increase in the Ter and Segre basins, albeit in a different way, throughout the first half of the century. NHN increases range from small to moderate in the 2020s to moderate to high in the 2040s. Dynamics would vary for the three basins and from crop to crop. The highest increases in NHN are found in the lower segments of the basins (excluding the lower Ter), where agriculture is spatially concentrated and more significant for the lower Segre.

Otherwise, the projected phenological changes could represent a greater constraint for crop productivity. Overall, the number of frost days will decrease in the three basins, while extremely hot days will increase. Growth cycles will begin earlier, and for some crops they will be shorter. A general advancement of the crop growing cycle has been shown throughout the future time horizons in this study. Moreover, a shortened crop growing cycle has been estimated in annual crops such as maize and temperate fruits such as grapevine although a prolongation of the vegetative season was predicted for some herbaceous crops opening new time windows for cropping as observed other authors (Tian et al., 2014; Trnka et al., 2011). Extreme events as increased heat days are projected for the three basins. Moreover, frost risk could increase due to advancement and shortening of the crop growing cycle (Darbyshire et al., 2013) despite decreasing frost days.

Upper segments of basins would experience the greatest climatic changes because they are the coldest and wettest. However, effects on crop production would be higher in the middle and lowest segments of basins since this is where most of the cropland is concentrated. The coastal effect leads to clear differences between the lower basin and the rest of the basin, except in the case of the Segre, as this is a tributary river and its lower course is clearly inland. The results in Chapter 4 supposes a fine-tuned approach due to is one of the few studies considering general and exhaustively projected changes in the NHN, phenology and growing cycle of major crops at a basin scale and considering the range of conditions in the region.

5.1.2 Comparison with other studies

Estimations in the present thesis are almost always in line with previous published studies to date assessing woody crops and agricultural soils sequestration potential and to assessing CC vulnerabilities for the different types of crops in the Mediterranean basin.

Although only a few studies on biomass carbon stocks on woody cropland were performed, most of them are in line with the results of Chapter 2 (Badalamenti et al., 2019; Iglesias et al., 2013; Keightley, 2011; Williams et al., 2011). Higher values for forest systems have often been reported in literature (Badalamenti et al., 2019; Gonzalez et al., 2015; Herrero and Bravo, 2012; Pasalodos-Tato et al., 2015; Vayreda et al., 2012a) but on occasions these values have been relatively close to those estimated here for the Mediterranean cropland. Mean C stock values differed from some studies in non-Mediterranean agricultural systems and other land uses (Asigbaase et al., 2021; Kongsager et al., 2013; Ortiz-Ceballos et al., 2020). However, close values were published as well for non-Mediterranean agricultural systems and globally (Kumar et al., 2010; Kuyah et al., 2012a, b; Kuyah et al., 2016; Zomer et al., 2016). Moreover, there are fewer studies on changes in land use (LUC) and the associated carbon sequestration rate (Huffman et al., 2015; Padilla et al., 2010).

Previous studies have succeeded in mapping SOC stocks at the topsoil over the study area (Chapter 3). This mean SOC stock value was near the values published for countries at similar latitudes according to (Minasny et al., 2017) that established SOC stocks fluctuate with latitude, insofar as they are greater at higher latitudes and humid tropics and lower in the mid-latitudes. Using a process-based model, (Alvaro-Fuentes et al., 2011) mapped SOC stocks in a wider area of NE Spain, showing values relatively far from our study in some land uses such as vineyard, olives or orchards. Notwithstanding all this, similar results have also been shown for annual and woody crops by other studies in Spain using geostatistical analysis (Rodríguez Martín et al., 2016). The resulting SOC stocks baseline map in the present study offers improvements regarding previous baselines covering the study area. Higher values were found in agricultural soils at northern or tropical latitudes (Adhikari et al., 2014; Bonfatti et al., 2016; Neufeldt, 2005). Lower SOC stock values have been published for agricultural soils in southern, semi-arid or arid regions (Albaladejo et al., 2013; Amirian Chakan et al., 2017; Hoyle et al., 2016; Muñoz-Rojas et al., 2017). Likewise, lower SOC stock values were estimated in Spanish soils in forest, shrubland and grassland systems estimated at 1 m depth by (Doblas-Miranda et al., 2013), maybe because these land uses are mainly encountered on shallower soils or steep slopes, whereas deeper soils and gentle slopes are preferable used for cultivated fields (Albaladejo et al., 2013; Lacoste et al., 2014) presenting a greater capacity to store SOC. Notwithstanding this, when only topsoil was considered, higher mean values were found under forests, shrublands and grasslands in Spain (Rodríguez Martín et al., 2016). In line with Chapter 3 findings, some authors (Albaladejo et al., 2013; Armas et al., 2017; Bonfatti et al., 2016; Chen et al., 2018) state that variable importance varies with depth. Climate, land use and management are likely to have a strong influence on SOC stocks at the topsoil, where these drivers directly impact. However, in the subsoil physico-chemical soil attributes are expected to be more crucial as drivers of SOC stocks than environmental factors. The importance of variables in explaining SOC stocks found here concurs with many studies where soil properties, climate and land use and management are seen to be the key factors. Several studies have highlighted the importance of climate in predicting SOC stocks. Conversely, other authors (Fantappie et al., 2011; Schillaci et al., 2017) show that changes in land use and management seem to have played a major role in the variations of SOC content.

Most crops in the three basins could experience a significant increase in NHN (Chapter 4) until mid-century with respect to the baseline period as shown by similar studies under Mediterranean (Iglesias and Garrote, 2015; Phogat et al., 2018; Savé et al., 2012; Valverde et al., 2015; Zhao et al., 2015) and non-Mediterranean conditions (Hong et al., 2016; McDonald and Girvetz, 2013). Similar values of annual NHN for wheat have been reported by (Saadi et al., 2015):

275 mm in inland area (Lleida) compared with 211.6 mm estimated in the present study for the lower Segre. Moreover, the results are in line with other studies that assess crop growing cycle and phenology (Koufos et al., 2018; Ruiz-Ramos et al., 2018; Saadi et al., 2015; Trnka et al., 2011).

5.1.3 Limitations of Estimations

Although several equations performed in this thesis (Chapter 2) were based on fairly good representative and even site-specific data for Mediterranean climates, specific allometries for some of the woody crops were lacked. Further efforts are required to improve the estimates by collecting site- and crop-specific data (biomass from olive and nuts, above all), considering a wide range of agricultural practices and traits (crop age, plant density, rainfed/irrigated, tree/vine architecture and training system and other) and refining modelling. Some limitations derived from information gaps in official agricultural census and registries were had to be handle throughout this thesis. Therefore, more efforts should be done by public stakeholders to maintain completed, updated and accessible crop-specific official census and registries.

The relatively low variance explained (27% and 20% for top and subsoil, respectively) when modelling SOC stocks (Chapter 3) can be explained by different reasons, together with their natural variability. Accuracy of soil data for the purpose of the thesis was partially limited. First, stoniness was estimated visually in field sampling and bulk density had to be estimated using expert-derived pedotransfer function from literature. Second, agricultural variables presented information gaps or generalizations that had to be estimated. Third, SOC stocks was assumed to remain stable over the 35-year sample-period, avoiding any consideration of possible CC effects during this time. Another limitation was the lack of information related to known factors controlling SOC stocks in terms of physical or chemical C protection (Fe and Al oxides, salinity, hydromorphy, pH or clay minerals), or in terms of soil disturbance, soil protection and C inputs, such as current and historical agricultural management practices. Finally, although soil samples are well distributed across

Catalan agriculture, some agricultural areas are poorly represented. Modelling prediction error and unquantified uncertainties associated with some covariate layers (in some cases, rasterized versions of polygonal mapping) used to map SOC stocks should also be considered. Residuals' spatial pattern of the model used for mapping SOC stocks at the topsoil evidenced regions presenting under- and over-predictions quite consistently. These regions need further attention.

Due to the methodology used in Chapter 4 for NHN estimations following Savé et al. (2012), some main limitations must be acknowledged that make it necessary to look at our results with some care. An important limitation is the effect on crop transpiration of increased CO_2 in the RCP 4.5 scenario was not considered in the NHN calculation. In fact, some authors (Elliott et al., 2014; Zhao et al., 2015) have highlighted the importance of considering increased CO_2. Estimations based on phenological and agroclimatic models that are valid in the reference period are implicitly assumed to be valid for the estimated periods. Moreover, the estimated changes in growing cycle in this study are based on growing degree days (GDD) accumulation, and changes in phenology for grapevines or maize use very simple models also based on GDD accumulation. Finally, the health status of the crop would undoubtedly affect these results, and pests and diseases are expected to increase in the Mediterranean as a result of CC (MedECC, 2020). Beyond this, crop performance will be affected by agronomical practices, local edaphic conditions and production needs, i.e., the market, which have not been included in the calculations. Moreover, results of this study are based on the expected conditions for current crops in the basins, thus, conclusions can be drawn about the degree of productivity of the current crops in their present locations.

5.2 Testing future management scenarios for the decision-making process

5.2.1 Designing ADAM strategies

Appropriate design of strategies and policies at all scales can contribute to ADAM. All the strategies that are focused on restricting global warming to 1.5 °C or below 2 °C require land-use changes and management. Land-use and spatial planning at the landscape level, policies and incentives or persuasive mechanisms (e.g., certifications or payments for sustainable production or ecosystem services) can achieve ADAM (IPCC, 2019). Diversification of the cropland landscape and food system can reduce risks of CC. The diversification of agriculture and markets and anticipating and planning for changes in the agro-food industry can reinforce adaptation (Tisdell and Wilson, 2019). A suite of cropland management strategies for the Mediterranean, including conservation of high-biomass cropland and the incorporation of woody crops in new areas to aid wildfire management may be necessary in order to meet goals for the near future in the study area. In fact, exacerbated by CC in the near future, carbon stock losses from wildfires could potentially exceed carbon sequestration at a local scale in Mediterranean forest ecosystems (Gonzalez et al., 2015). Land management has a significant part to play in ADAM strategies, especially in adaptation, through landscape approaches (new crops, land use changes, mosaic landscape, agroforestry, etc.) directed towards CC risks. Therefore, generating knowledge about CC impacts and risks can be very useful for land managers in the decision-making process. Land management approaches can be instrumental in creating ADAM synergies; however, caution is required when applying land use scenarios, because barriers to adaptation and limits to their contribution to mitigation could appear in certain regions.

ADAM strategies should also contemplate sustainable dietary choices and food waste issues (IPCC, 2019). Balanced diets (plant-based and animal source diets from sustainable and low-carbon systems) show better opportunities for ADAM and public health co-benefits (Milner et al., 2015; van de Kamp et al., 2018). Transitions towards low-carbon diets may be influenced by policies promoting sustainable local practices or cultural habits and imposing limitations, e.g., financial barriers. Influencing dietary choices by improving nutrition based on public health guidelines, promoting food diversity in public spaces and through financial incentives or advertising campaigns can lead to more sustainable land management and contribute to achieving ADAM goals. At present, approximately 25% of all food produced is lost or goes to waste (Alexander et al., 2017). Thus, the reduction of food waste can contribute to ADAM by reducing the use and consumption of natural resources required for food production such as land or water. Improved technical options in harvesting, storage, transport or packaging and investment in education can reduce food loss and waste, freeing up several Mkm^2 of land (IPCC, 2019).

Moreover, socio-economic and ecological co-benefits can be obtained by planning and implementing ADAM strategies in the near future, helping to reduce vulnerabilities in the agro-food system, creating more resilient systems, reducing land degradation and lowering the risk to millions of people.

The success of ADAM strategies can be improved if local stakeholders are involved, while always taking account of local environmental and socio-economic conditions. Involving appropriate stakeholders is crucial to the identification of impacts. Local agricultural knowledge can help to address CC challenges. Furthermore, ADAM strategies should maximize synergies between adaptation, mitigation and socio-economic profits by preserving ecosystem services. The application of multiple ADAM strategies is crucial to achieving objectives and no single measure would be sufficient on its own (Friedlingstein et al., 2019).

5.2.2 Agricultural and land management practices for Adaptation and Mitigation

Stabilizing atmospheric GHGs concentrations is the great challenge of the century. To reduce emissions and/or remove GHGs from the atmosphere, different mechanisms can be used. Through the adoption of certain agricultural practices or land use changes, some quantities of the emitted carbon can be sequestered by agricultural or natural sinks (soils and woody biomass), mitigating CC by increasing carbon stocks. However, crop carbon sequestration will be slowed down due to soil carbon saturation and crop aging, and they could be reversed or suffer losses due to certain environmental conditions and disturbances (floods, droughts, fires, or pests) or deficient management. As mentioned above, some actions that contribute to ADAM in cropland include adding organic matter to soil, controlling erosion, improving fertilizer and crop management, and using genetically improved varieties for stress tolerance (IPCC, 2019). ADAM solutions are site-specific and should include water management (for example, water harvesting or efficient irrigation), restoring degraded land using drought-resilient plant and crops, agroforestry and other agroecological adaptation practices (IPCC, 2019). Adaptation measures and strategies should be consistent and based on empirical information to reduce future impacts of CC and facilitate the design of more resilient agricultural water management systems. These measures mainly consist in: i) changing the water management scheme; ii) changing the crop distribution and crop choices such as low water demand crops (Allain et al., 2018; Mo et al., 2017; Ronco et al., 2017); iii) applying support or supplementary irrigation (Dechmi and Skhiri, 2013; Ruiz-Ramos et al., 2018); iv) adjusting irrigation to net irrigation requirements (Allain et al., 2018; Dechmi and Skhiri, 2013); v) adjusting sowing dates and the cropping calendar (Rötter et al., 2013; Ruiz-Ramos et al., 2018); and vi) changing to cultivars or crops more suited to adverse conditions (Mo et al., 2017; Ronco et al., 2017). These measures also form part of a water management strategy that strongly considers a future scenario characterized by higher demands together with decreased water availability, which is highly plausible. Many other adaptation measures and strategies should be taken into account as well, such as: i) reduction in meat consumption through lower-carbon diets (Vanham et al., 2016); ii) changes in land use and forest management to regulate water availability for the basin (Zabalza-Martínez et al., 2018); iii) rainwater harvesting and storage (Rockstrom, 2000); iv) reuse of wastewater in agriculture (Panagopoulos et al., 2014; Ronco et al., 2017); v) crop diversification and crop rotation by alternating water-demanding crops with crops demanding less water (Allain et al., 2018; Lin, 2011); vi) conservation agriculture (Prestele et al., 2018); or vii) physically protecting crops from adverse events by establishing abatement infrastructures.

Strategies reducing soil erosion, carbon and nutrient loss and increasing SOC stocks include, among others, green manure, cover or service crops (Garcia et al., 2018; Vicente-Vicente et al., 2016), crop residue incorporation (Almagro et al., 2017), reduced/zero tillage (Almagro et al., 2017; Alvaro-Fuentes et al., 2009; Alvaro-Fuentes et al., 2012b; Iocola et al., 2017), improved grazing (Chen et al., 2015), hedgerows and uncropped field margins (D'Acunto et al., 2014; Drexler et al., 2021; Viaud and Kunnemann, 2021), organic farming (Aguilera et al., 2013; Blanco-Canqui et al., 2017; Brunori et al., 2016) and conservation agriculture (Gonzalez-Sanchez et al., 2012; Sun et al., 2020). Moreover, biochar addition sequesters carbon (Andrés et al., 2019; Majumder et al., 2019; Windeatt et al., 2014) and improves soil conditions (Baronti et al., 2014), so it could be an interesting option for some soils and climates. In fact, biomass from crop residues or permanent structures of woody crops when harvested can be converted into biochar and added to the soil.

Best management practices for carbon sequestration and adaptation in some systems, such as dryland agriculture, depend on local conditions (IPCC, 2019). Some ADAM strategies can generate trade-offs and become maladaptive due to their impacts. For example, irrigation could cause soil salinization or water source depletion, and afforestation and reforestation in water-limited regions of the Mediterranean basin could cause degraded ecosystems, water availability issues and disturbances endangering the increasing trend of forest as a carbon sink (Falloon and Betts, 2010; Friedlingstein et al., 2019; Vayreda et al., 2012b).

5.2.3 Drawing and testing Adaptation and Mitigation scenarios at the regional level.

Drawing and testing prospective scenarios for CC, landscape evolutions and application of certain agricultural practices could offer the possibility of identifying risks and improving the design of

strategies. Several scenarios are often adopted to better illustrate the uncertainty in projections (Carter and La Rovere, 2001). As Bouroncle et al. (2017) state, performances based on spatial visualization using legacy and available data are useful frameworks for assessing comparative scenarios, they help to identify opportunities and vulnerabilities, and they can identify actions for ADAM strategies.
With regard to C stocks, the impact on both soil and standing vegetation C stocks should be examined in different land use trends (current, business as usual or land uses for ADAM) and agricultural management scenarios (cover crops, reduced tillage, green manure, organic fertilization, crop residue incorporation, improved grazing or field margins and hedgerows) right across the study area under different global climate models and CC scenarios for future decades. For example, promoting woody crops instead of annual crops could provide greater carbon sequestration potential due to the longer lifespan of trees or vines. Furthermore, harvested wood from permanent crops could be transferred to wood products, storing carbon over the long term and reducing emissions, or it could be used for energy (IPCC, 2019). Although harvested woody biomass used for energy production rapidly releases carbon into the atmosphere, it also avoids and reduces burning of fossil fuels.

Otherwise, it will be necessary to adopt new water use and management strategies in the study area, in order to maintain yields and improve agriculture. For example, as well as increasing general irrigation efficiency, always adjusting irrigation to hydric needs and not to a predetermined concession should form part of a water management strategy in a water and land governance framework. The decision to use low water demand crops or varieties should not simply be left to the growers, but it should also be included in a water governance scheme, together with restricting the area of higher water consuming crops or defining support irrigation protocols to ensure crop survival in the driest years. The impacts of CC in the three basins studied in chapter 4 could result in significant limitations for crops, if adaptive strategies beyond irrigation and growing cycle issues are not applied. As a matter of fact, choosing site-specific measures and combining them are the most appropriate options when seeking to adapt agricultural systems to CC measures (Dechmi and Skhiri, 2013; Ruiz-Ramos et al., 2018).

Moreover, the implementation of policies, including water management, with a combination of CC mitigation and adaptation measures is highly recommended in order to make agricultural systems more resilient and obtain high yields (FAO, 2013).

All the strategies referred to above are fully in line with Spain's new EU CAP (Common Agriculture Policy) Strategic Plan. Up until now, CAP strategies in Spain had mainly focused on promoting higher payments for the most intensive or highest yielding farms, while nothing was done to alleviate CC risks. Most of these farms have irrigated crops and are located in drylands vulnerable to CC impacts; furthermore, they are creating other vulnerabilities all over the region by consuming water from depleted freshwater sources. Fortunately, the new CAP has incorporated conditionality and eco-schemes for climate and energy, and it should introduce sustainable practices including environmental and social issues and promote climate, nature and animal friendly agricultural practices.

To date, several studies have predicted mitigation scenarios at the regional scale considering different CC scenarios, land cover and certain agricultural management practices (Alvaro-Fuentes et al., 2012a; Alvaro-Fuentes and Paustian, 2011; Bleuler et al., 2017; Caddeo et al., 2019; Chen et al., 2018; Holder et al., 2019; Jost et al., 2021; Kaczynski et al., 2017; Lacoste et al., 2016; Lugato et al., 2014; Pardo et al., 2017; Rial et al., 2017; Wiesmeier et al., 2016; Yigini and Panagos, 2016; Zhang et al., 2017). More recently, some authors have studied different scenarios to test the feasibility of the 4x1000 strategy in certain regions of Europe (Bruni et al., 2021; Wiesmeier et al., 2020). There are quite a few studies testing climate adaptation scenarios in literature. Most of these have focused on CC scenarios and land use (Lungarska and Chakir, 2018), land and water use (Jäger et al., 2015; Pfister et al., 2011; Pham et al., 2021), irrigation and water management (Babaeian et al., 2021; Esteve et al., 2015; Staccione et al., 2021), or varieties and crop change (Zabel et al., 2021). However, very few studies have tested scenarios on ADAM taking account of their synergies and trade-offs (Mu et al., 2015).

5.3 Testing scenarios: an example of mitigation strategy for manure management in Catalonia.

As an example of testing mitigation strategy, we carry out a simple approach published in Kamilaris et al. (2021). In this paper, we performed a simulation using the area of Catalonia as a case study for the characteristic low SOC in the Mediterranean, to examine whether animal manure can improve substantially the SOC of agricultural fields, when applied as organic fertilizers. The aim of this approach is to demonstrate if agriculture, and in particular agricultural soils, can play a crucial role where food security and CC are concerned by increasing soil organic matter stocks by 4 per 1000 (or 0.4%) per year as a compensation for the global emissions of greenhouse gases by anthropogenic sources (Minasny et al., 2017).

The present study assesses the application of organic matter in agricultural soils as an option of carbon sequestration strategy at the regional scale, also considering the problems associated to manure characteristics, transportation and application. The economic footprint has also been considered in this assessment. This would allow to assess the feasibility of reaching the 4x1000 target by means of animal manure used as agricultural fertilizer. To simplify the problem, the geographical area of Catalonia, as one of the European regions with the highest livestock density, has been divided into a two-dimensional grid (cells of 1 km^2). In this way, the distances between livestock farms (i.e., original grid cell) and crop fields (e.g., destination grid cell) are easier to compute, considering straight-line grid cell Manhattan distance as the metric to use. Each crop field and livestock farm has been assigned to the grid cell where the farm is physically located. For every livestock farm, the yearly amount of manure produced and its equivalent in nitrogen as fertilizer have been calculated, depending on the type and number of animals on the farm, based on the IPCC guidelines (TIER1; IPCC, 2006). Similarly, for every crop field, the yearly needs in nitrogen have been computed, depending on the crop type and total hectares of land, according to the Nitrate Directive (91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources). The estimated total fertilizer needs of crop fields (i.e., 88,000 tons of nitrogen) were lower than the availability of nitrogen from animal manure (i.e., 116,000 tons of nitrogen). This means that the produced amount of manure/nitrogen from livestock agriculture has the potential to completely satisfy the total needs of crop farms. Further, we needed to know the existing agricultural soil organic content (SOC) around Catalonia and to associate this with the existing crop fields. This information was retrieved from the SOC stock baseline map for Catalonia generated in Chapter 3 of this thesis and published by Funes et al. (2019). The correlation with crop fields was performed through Geographical Information System techniques. Finally, it was necessary to estimate the carbon content by applying animal manure to soils. For each grid cell, we are aware of the crop and livestock farms located inside that cell, the manure/nitrogen production (i.e., from the livestock farms) and the needs in nitrogen (i.e., of the crop fields). Moreover, some crop farms in Catalonia fall within nitrate vulnerable zones. Inside these zones, only a maximum of 170 kg/ha (i.e., kilos/hectare) of nitrogen from manure can be applied. We assumed that each transport vehicle (i.e., truck) used for the transfer of manure has a limited capacity of 20 cubic meters to transfer manure/nitrogen. The allowed periods of the year when fertilizer can be applied on the land (depending whether the crop falls within a vulnerable area or not) based on the Directive 153/2019 of the Government of Catalonia, were also considered. To solve the manure transfer problem from livestock farms to crop fields in an optimal way, a centralized optimized approach (COA) has been developed (Kamilaris et al., 2020), based on an algorithm that generalizes and adapts the well-known Dijkstra's algorithm for finding shortest paths (Cherkassky et al., 1996), together with the use of origin-destination cost matrices as applied in the travelling salesman problem for choosing best routes. COA solves the problem by considering a shortest-path problem on an undirected, non-negative, weighted graph. To use the algorithm within the context of the problem under study, the algorithm has been modified to respect the necessary configurations and constraints, i.e., by modelling the weights of the graph to represent both transport distances and crop farms' nitrogen needs. All combinations of visits to nearby farms (within a wide radius of 60 kilometers) are added to an origin-destination cost matrix, where the most profitable route is selected. A total of 106,000 Mg of carbon is indirectly stored into

10,982 fields of 19 different crop types, spread at a total area of 390,000 hectares.

The mean value of carbon added in each crop field where animal manure was applied was 0.29 kg C/m^2 as a consequence of applying mean doses of animal fertilizer around 1.34 kg/m^2. The present study found that applying animal manure as a single strategy to increase SOC stocks in Mediterranean agricultural soils in Northeastern of Spain would be not enough to reach the 4x1000 goals in a duration of one year in most of the crop fields (Fig. 1).

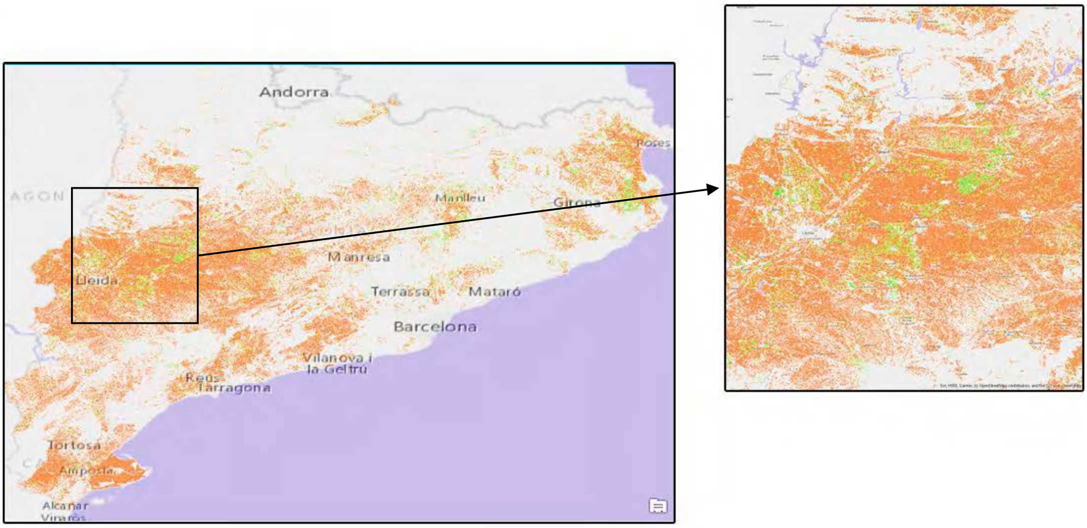

Figure 1. Map of Catalonia showing the crop fields of the region. The fields satisfying the 4x1000 strategy at the first year of the manure transfer program are shown in green color, the rest fields in brown color. The region near the city of Lleida is magnified at the right side. Source: Kamilaris et al., (2021).

The fact of improving only certain regions could be associated to the concentration of livestock farms in specific areas and to the fact that pig slurry, containing low carbon content, is the major animal fertilizer produced in Catalonia. In order to increase the possibilities to achieve the 4x1000 strategy and prevent ground water pollution by nitrogen, it would be necessary to apply composted manure that contains higher content of carbon. It is true that soil is a very important carbon sink, but the application of 4x1000 must be accomplished according to new integrated models of agriculture, in which sources and sinks of carbon will be closed. The method of transferring manure needs to be combined with other strategies, such as those cited other studies above in previous section (5.2.2): cover crops, crop rotation, reduced tillage, crop residue incorporation to the soil, among others.

Our study has some limitations. Soil organic matter for some animal manure types has been calculated in several studies outside Europe (India, China), as well as in Catalonia and at different soil depths. Moreover, the effect of manure management systems (treatment units for pig slurry, compost units for bovine manure) was not considered. In addition, only the first year of manure application is actually assessed. Long-time periods have been considered only naively, without considering weather/climate modelling/forecasting. Climate variables and soil properties are important drivers of SOC dynamics (Funes et al., 2019), but have not been considered in the calculations, even in the first-year case of applying the proposed approach.

Future efforts should focus on considering the effects of: i) precipitation/temperature changes using different climate change scenarios; ii) land uses changes; iii) more realistic models to calculate the SOM based on animal manure; iv) manure management systems and multiple years; and v) CO_2 emissions due to manure transportation from livestock farm to crop field.

Overall, the results implies that the proposed approach needs to be combined with other mitigation actions strategies, without forget adaptation and aside from facing all the limitations exposed.

5.4 Future research

Future research should focus primarily on improving estimations and data quality on carbon stocks, in order to improve modeling and reduce prediction uncertainties.

Overall, carbon stock estimations in woody crops should be enhanced by improving crop- and site-specific equations and allometries (Chapter 2). Future soil sampling efforts should be centered around the acquisition of better SOC data (Chapter 3), as well as the collection of as many potential explanatory variables as possible (bulk density, proportion of coarse particles, detailed soil analytics, exact geographical position, detailed land use, past and current agricultural management practices, etc.). Moreover, further work must be undertaken to understand the role of abiotic, biotic and human factors affecting spatial distribution of SOC stocks not considered (Chapter 3), and to spatially represent SOC stock predictors at a reasonably good spatial resolution, especially soil properties (soil texture, clay content, soil type or depth to bedrock). Additionally, greater efforts should be made to integrate the results of the assessment of CC impacts on crop NHN (Chapter 4) with hydrological modeling for future climate and land use scenarios that will make it possible to estimate the gap (the deficit or imbalance) between agricultural water supply and demands in the area, and to design water management strategies. Furthermore, a comprehensive regional assessment of CC vulnerability and impacts integrating the range of current and potential future crops at the basin level has yet to be made.

Modeling work also becomes necessary for the purpose of spatially simulating and testing different initiatives and/or scenarios (concerning water management, land use changes, best management practices in agriculture and CC scenarios) at the basin or regional scale, in order to test different adaptation and mitigation strategies for Catalonia that will lead to the formulation of targeted policies under Mediterranean conditions. Therefore, what is clearly required is future work on testing scenarios combining land use change strategies, best management practices for increasing carbon sequestration and enhanced crop resilience, and a wide range of plausible climate scenarios at the local and regional level. Account should also be taken of both the EU Green Deal, which promotes organic agriculture, and the EU strategy Farm to Fork, which encourages healthy food. In this context, it will be necessary to have some predictive and prospective models for crop productivity. These must be focused on the climate impacts on metabolism, phenology, and both multi biotic and abiotic environmental factors.

5.5 Conclusions

- This thesis has generated new and updated empirical knowledge by: i) performing crop- and site-specific equations to estimate carbon stocks in woody biomass and changes in these during the 2010s; ii) producing spatial estimates of SOC stocks in agricultural soils, identifying the major SOC drivers and their spatial variability; and iii) estimating the main impacts of climate change on NHN and agroclimatic and phenology indicators at the sub-basin level.

- Based on available crop and site-specific data, two model based maps were generated, namely the carbon stock for agricultural woody biomass map and the agricultural SOC stock map; both contributed to improving the spatial estimates of regional carbon balances. The biomass carbon stock estimated for woody crops in Catalonia was 5.40 Tg C, with an average of 16.44 Mg C/ha. Agricultural SOC stocks in Catalonia contain 48.8 Mg C/ha, three times more than carbon stocks of woody crop biomass.

- During the 2010s, carbon stock in the biomass of woody crops showed an annual increase of 3.8% (+0.17 Tg C/year) due to growth of remaining woody cropland, despite a decrease in the area of woody crops (-2.8%/year).

- SOC stock drivers differed between top- and subsoil. Topsoil offers management opportunities for C sequestration, since this soil layer is mainly affected by dynamic variables (texture, climate, and agricultural land use). Moreover, drivers' effects on SOC stocks vary spatially at the regional scale, implying that mitigation strategies should be adjusted at the local scale.

- In the three Mediterranean basins studied, crops could be highly impacted before the middle of the century, even with a moderate climate change scenario (RCP 4.5). NHN of the main crops in the basin are expected to increase due to both an increase in crop potential evapotranspiration and a decrease in precipitation during the growing season. In view of reduced water availability throughout this century, the projected impacts on water needs could challenge the feasibility of maintaining the current agricultural model in the study area, even in irrigated areas (35% of total agricultural area).

- A general advancement and shortening of the productive cycle, lengthening of the vegetating season, impacts on phenology and damages associated with extreme temperatures were forecast for around 2050.

- The projected impacts on agriculture in Catalonia open up new possibilities for a wide range of adaptation measures that should form part of any water management scheme within a governance framework.

- The results of this thesis can be applied to evaluate the carbon consequences of land and agricultural management, to pinpoint the impacts of climate change on agriculture and to identify agricultural vulnerabilities. Overall, a baseline framework is provided for designing climate change mitigation and adaptation strategies.

- This thesis offers a starting point for the simulation of adaptation and mitigation scenarios that will be instrumental in the design of more resilient agricultural systems in Catalonia, including carbon stock and water management, and its findings could be partially extrapolated to many other regions of the Mediterranean basin.

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Appendix

Chapter 2

Appendix A

Supporting Figures

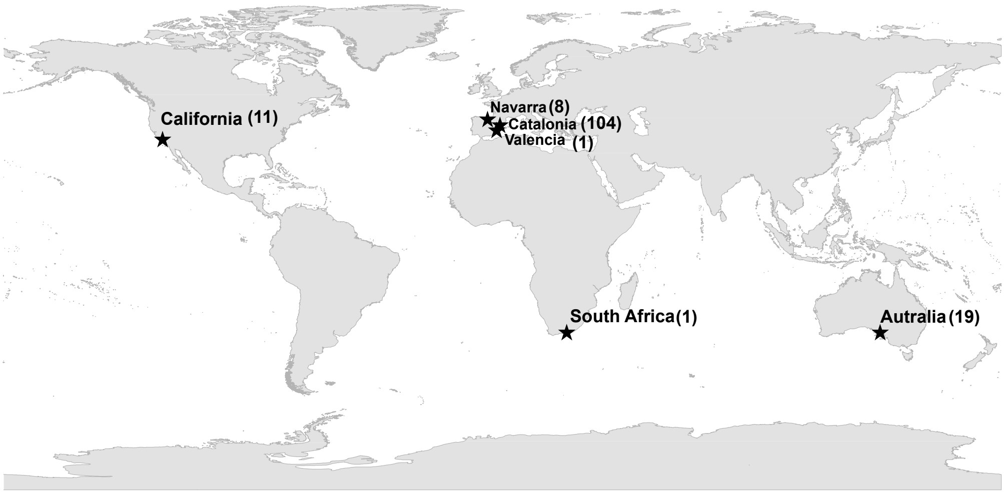

Figure A.1. Areas with Mediterranean conditions and dataset size (in brackets) from each area used to build grapevine equation.

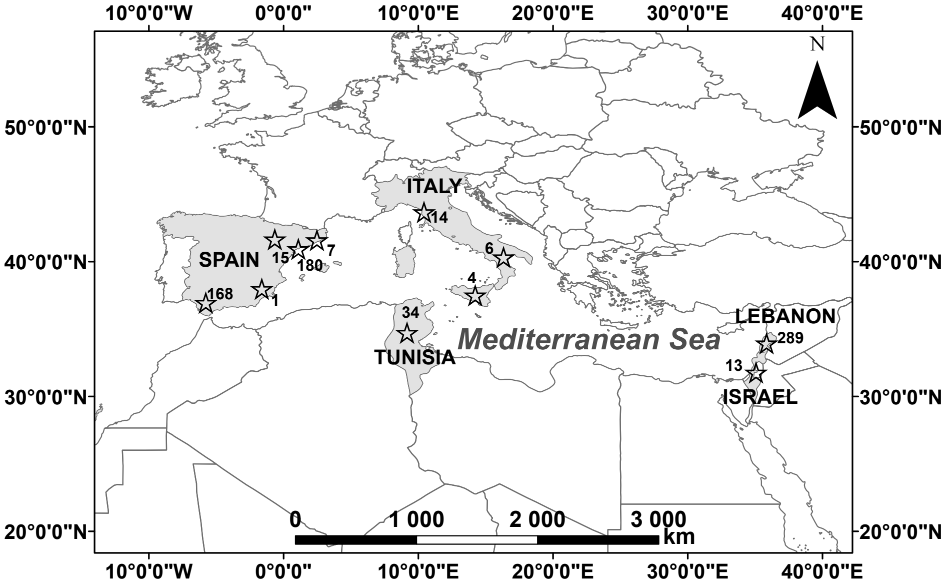

Figure A.2. Areas in the Mediterranean basin and dataset size (numbers) from each area used to build olive equation.

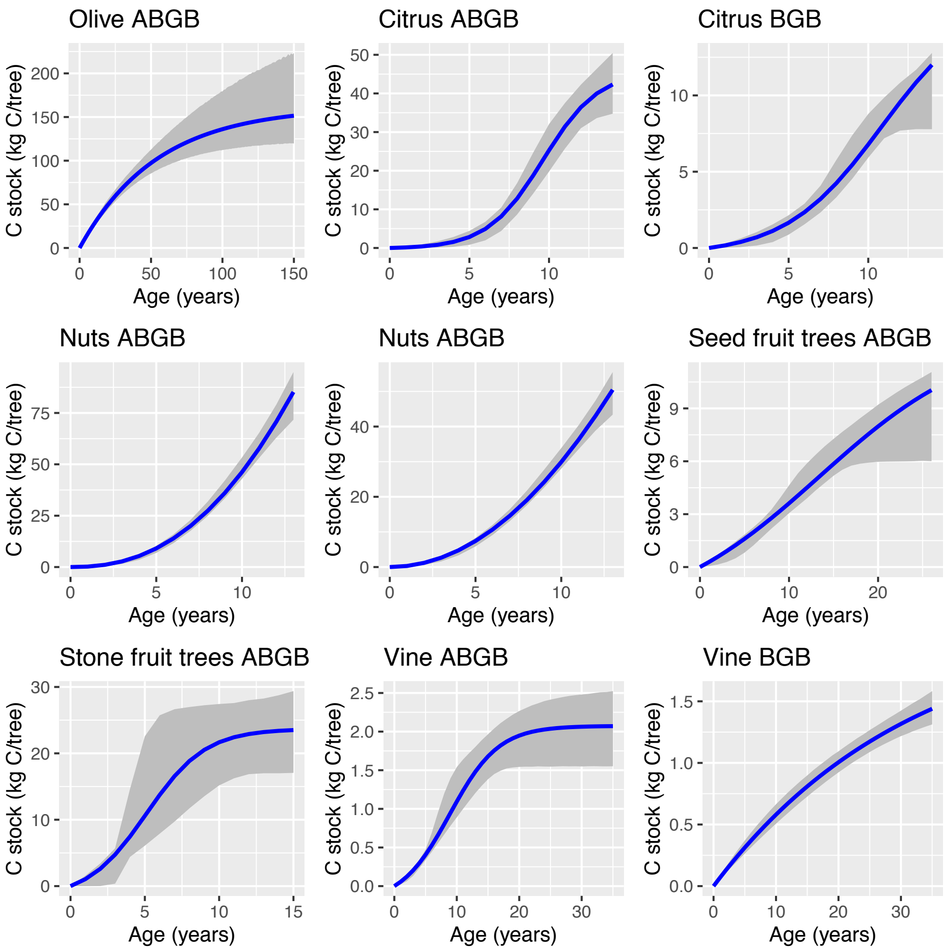

Figure A.3. Carbon stock as function of crop age (kg C/tree; blue line) and 95% confidence of interval (grey zone) in ABGB or BGB of woody crops. Confidence of interval represents the error propagation to carbon content estimation at ABGB and BGB level.

ABGB: Aboveground Biomass

BGB: Belowground Biomass

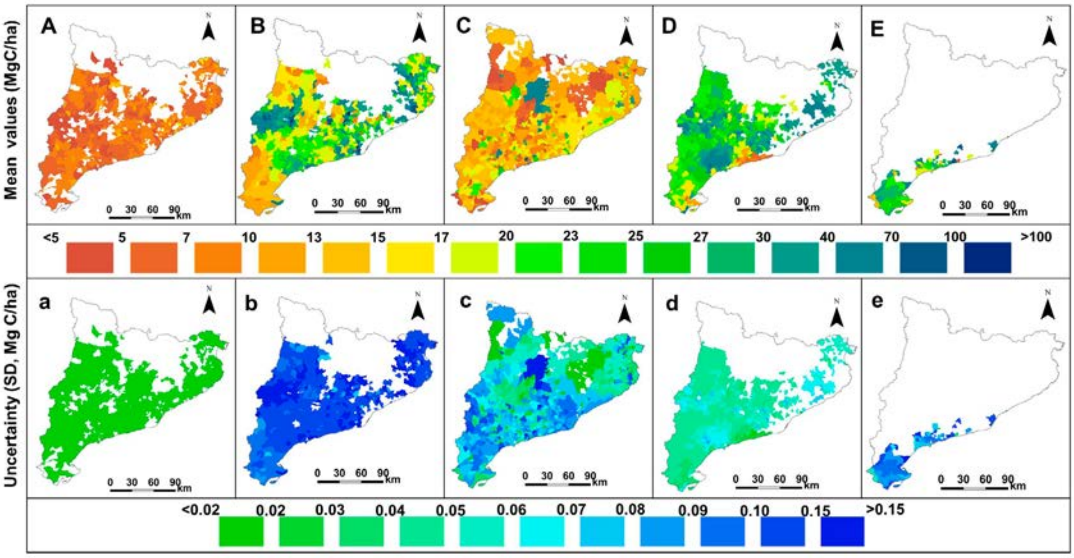

Figure A.4. Spatial distribution of average biomass carbon change (Mg C/ha) in Catalonia for woody crops for the year 2013: A) Grapevine, B) Olive, C) Fruits, D) Nuts, E) Citrus. Spatial Distribution of uncertainty (standard deviation, SD) of the estimations: a) Grapevine, b) Olive, c) Fruits d) Nuts and e) Citrus.

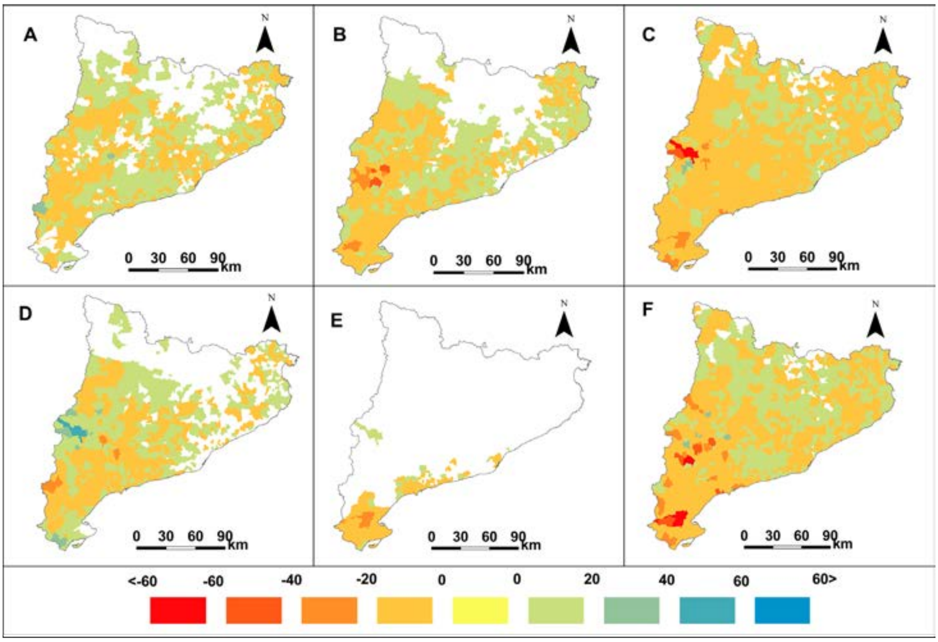

Figure A.5. Spatial distribution of cropland change (ha/year) from 2013 to 2019 in Catalonia for woody crops at the municipality level: A) Grapevine, B) Olive, C) Fruits, D) Nuts, E) Citrus and F) Total woody crops.

Chapter 2

Appendix B

Supporting Tables

Table B.1. Detailed information of the dataset for aboveground grapevine biomass.

Data source	Location	Reference	Sample Date	Dataset size	Crop Age (years)	Culture traits available information
Literature data	California	*Williams et al. (2011)*	-	5	3;7;12-14	Irrigated; 2500 vines/ha and organic culture
		Mullins et al. (1992)	1986	1	10	‘Chenin Blanc’ cultivar; double cordon training system; 1736 vines/ha
		Williams (1996)	-	1	7	‘Thompson Seedless’ cultivar and 1157 vines/ha
		Williams & Biscay (1991)	1988	1	18	‘Cabernet Sauvingon’ cultivar and 5C rootstock
		Keightley et al. (2011)	2006	1	8	‘Sangiovese’ cultivar, Zinfandel rootstock; 1494 vines/ha
		Araujo et al. (1995)	1985-1986	2	3	‘Thompson Seedless’ cultivar, irrigated, cordon training system and 1157 vines/ha
	Southafrica	*Saayman & Huyssteen (1980)*	-	1	12	‘Cabernet Blanc’ cultivar and 101-14 MGT rootstock
	Australia	*Clingeleffer & krake (1992)*	1985-187	1	15	‘Cabernet Franc’ cultivar, T-trellis training system, 1388 vines/ha
		Goward (2012)	-	18	2;13;14	‘Chardonnay’, ‘Sauvignon Blanc’, ‘Riesling’, ‘Shiraz’, ‘Merlot’, ‘Cabernet Sauvignon’, ‘Pinot Noir’ and ‘Pinot Gris’ cultivars; irrigated; double cordon training system; 1653-2722 vines/ha
	Spain	*Escolana et al. 2012*	-	16	1	‘Cabernet Sauvignon’, ‘Malvasia’, ‘Tempranillo’ and ‘Garnacha’ cultivars; irrigated, seedling container
		Santesteban & Royo (2006)	1998-2000	1	7	‘Tempranillo’ cultivar; 110 R rootstock; irrigated; 2655 vines/ha
		Santesteban et al. (2011a)	2003-2006	2	5	‘Tempranillo’ cultivar; controlled irrigation; 110R rootstock; 3333 vines /ha
		Santesteban et al. (2011b)	2004-2005	1	7	‘Tempranillo’ cultivar; 1103P rootstock; 3333 vines/ha
		Santesteban et al. (2013)	2008	2	6	‘Tempranillo’ cultivar; irrigated; 110R rootstock; 2680-3636 vines/ha

Cont. Table B.1.

Data source	Location	Reference	Sample Date	Dataset size	Crop Age (years)	Culture traits available information
Non-destructive measurements	Caldes de Montbui (Barcelona, Spain)	Own measurements	2011	14	3	‘Grenache’ cultivar; rainfed and irrigated culture; 110R, 41B and 140RU rootstocks; double cordon training system; 2222 vines/ha
	Caldes de Montbui (Barcelona, Spain)	Own measurements	2013	8	6;22	‘Merlot’, ‘Grenache’, ‘Tempranillo’ and ‘Cabernet Sauvignon’ cultivars; rainfed and irrigated culture; 110R, 41B and 161-49 rootstocks; double cordon training system; 1667-2222 vines/ha
Destructive measurements	Caldes de Montbui (Barcelona, Spain)	Own measurements	2006-2008	63	1;2;3	‘Grenache’ cultivar; rainfed and irrigated culture; 110R, 41B and 161-49 rootstocks; double cordon training system; 2222 vines/ha
	Caldes de Montbui (Barcelona, Spain)	Own measurements	2011	14	3	‘Grenache’ cultivar; rainfed and irrigated culture; 110R, 41B and 140RU rootstocks; double cordon training system; 2222 vines/ha
	Penedés (Barcelona, Spain)	Own measurements	2006; 2008	5	25; 35	‘Cabernet Franc’ and ‘Cabernet Sauvignon’ cultivars; rainfed; double cordon training system; 41B rootstock; 2976 vines/ha
	Navarra (Spain)	Donated data (data not published)*	2007	2	19;14	‘Tempranillo’ and ‘Grenache’ cultivars; rainfed and 2222-3030 vines/ha

Table B.2. Detailed information of the data set for olive Trunk Cross-Sectional Area (TCSA).

Data source	Location	Reference	Sample date	Dataset size	Crop age (years)	Available culture traits information
Literature Data	Talkesa (Tunisia)	Larbi et al. 2012	2009	4	7	‘Arbequina’ cultivar; irrigated; from 312 to 1250 trees/ha
	Aragón (Spain)	Aragués et al. 2005*	1999-2001	3	2	‘Arbequina’ cultivar; Irrigated; saline soil; 1400 trees/ha
	Aragón (Spain)	Aragués et al. 2010*	2003-2007	12	2;6	‘Arbequina’ and ‘Emprete’ cultivars, 727 trees/ha; watered with different salinty concentrations
	Montsià region (Spain)	Arnan et al. 2012*	2007-2008	4	37;94;101;104	Rainfed
	Israel	Segal et al. 2011*	2006-2009	12	4-9	‘Barnea’ and ‘Leccino’ cultivars; irrigated; 900 trees/ha
	Murcia (Spain)	Almagro et al. 2010*	-	1	100	‘Lechin de Granada’ cultivar; rainfed; 107 trees/ha
	Kibbutz Revivim (Israel)	Bustan et al. 2011*	2005-2006	1	10	‘Barnea’ cultivar; irrigated; 360 trees/ha
	Sicily (Italy)	Nardino et al. 2013	-	4	12;16;150	‘Nocellara del Belice’ cultivar; irrigated; 204-250 trees/ha
	Pisa (Italy)	Gucci et al. 2012	2006-2010	14	2-8	‘Frantoio’ cultivar; deficit irrigation; 513 trees/ha, tillage and natural cover, minimum pruning criteria
	Seville (Spain)	Fernandez et al. 2011a	-	3	12	‘Arbequina’ cultivar; irrigated; 238 trees/ha; diferent irrigation systems.
	Sfax region (Tunisia)	Mezghani et al. 2012	2008-2009	30	5	‘Picholine’, ‘Meski’, ‘Ascolana’, ‘Manzanille’, ‘Chemlali’, ‘Chetoui’, ‘Luccio’, ‘Souri’, ‘Koroneiki’ and ‘Coratina’ cultivars; 202 trees/ha and different irrigation systems
	Basilicata (Italy)	Palese et al. 2010	1997-1999	6	7-9	‘Coratina’ cultivar, irrigated and rainfed systems; 556 trees/ha
Non-destructive Measurements	Barcelona (Spain)	Own measurements	2013	3	11	‘Arbequina’ cultivar; irrigated; 370 trees/ha
	Barcelona (Spain)	Own measurements	1997-2000	4	1	‘Arbequina’, irrigated, container seedlings
	Tarragona (Spain)	Donated data by Agustí Romero; Fruit Production Program (IRTA)	2002-2010	176	4-12	‘Arbequina’, ‘Cornicabra’, ‘Empeltre’, ‘Frantoio’, ‘Hojiblanca’, ‘Kalamata’, ‘Oblonga’, ‘Picual’, ‘Picudo’, ‘Plans’, ‘Solà’ and ‘Valentins’ cultivars; irrigated and rainfed systems; 204 trees/ha
	Seville (Spain)	Donated data by J.E. Fernandez (IRNAS-CSIC)	1996-1997;2000; 2002-2007; 2009; 2012	105	6;12;29;30; 33; 35-39	‘Arberquina’ and ‘Manzanille’ cultivars; different irrigation doses and rainfed; from 286 to 1667 trees/ha (detailed information of some of these data in Fernadez et al. , 2011b*)
	Lebaa, Abdeh and Tyr (Libanon)	Donated data by Milad El Raichy	2013	29	16;17;20; 38;47	‘Nabali’, ‘Manzanilla’, ‘Picholine’, ‘Ascolana’, ‘Soury’, ‘Baladi’, ‘Edlbi’, ‘Bella di spagna’, ‘Sorani’, ‘Ayrouni’ cultivars; different irrigation systems and rainfed; from 237 to 833 trees/ha

*data non published donated by the author

Table B.3. Detailed information for fruit trees biomass dataset: seed and stone trees

Non-Citrus Type	Data source	Location	Reference	Sample date	Dataset size	Crop age (years)	Available culture traits information
Seed-fruit	**Non-destructive measurements**	IRTA-Mas Badia facilities (Girona)	Own measurement	2014	30	1-11;13-15; 20;26	‘Gala’, ‘Golden’ and ‘Granny Smith ‘apple cultivars; irrigated, M-9 NAKB, M-9 M-9 Pajam 1, M-9 EMLA and MM-106 rootstocks; central leader training system; 2040-2666 trees/ha
	Destructive measurements	IRTA facilities (Lleida)	Donated data* by IRTA Fruit Production Program	2010	6	10-11	‘Golden’ and ‘Galaxy’ apple cultivars and ‘Williams’ and ‘Conference’ pear cultivars; irrigated; M-9 NAKB ,M-9 and M-C rootstocks; central leader training system; 1250-2500 trees/ha
Stone-fruit	**Literature**	Basilicata Region (South Italy)	Sofo et al. (2005)	1997-2001	8	2-5	‘Springcrest’ peach cultivar; drip irrigation; GF677 rootstock; delayed vase and transverse Y training systems; 416-1111 trees/ha
		Bologna (Italy)	Bravo et al. (2012)	2009	4	2	‘Orion’ nectarine cultivars, drip irrigation; GF677 rootstock; 40L containers
		California	Grossman and Dejong (1994)	1990-1991	1	7	‘Cal Red’ peach cultivar; irrigated; central leader training system; 1250 trees/ha
		Sicilia (Italy)	Caruso et al. (1999)	1992-1994	6	2-4	‘Flordaprince’ peach cultivar; irrigated; GF677 rootstock; central leader and Y training systems; 930-1850 trees/ha
		California	Solari et al. (2006)	2002	4	1	‘Mayfire’ peach cultivar; micro-sprinkler irrigation; K146-43; Hiawatha and Nemaguard rootstocks
		South Italy	Inglese et al. (2002)	1998-1999	8	1-2	‘Early May Crest’ peach cultivar; irrigated; GF677 and Penta rootstocks; 230L containers
		Zaragoza (Spain)	El-Jendoubi et al. (2013)	2007-2010	3	14	‘Babygold5’ , ‘Catherina’ and ‘Calanda’ peach cultivars; GF677 rootstock; flood irrigation; open vase training system; 500-670 trees/ha
		Sicilia (Italy)	Caruso et al. (2001)	1998-1999	2	1-2	‘Maycrest’ peach cultivar; GF677 and Missour rootstocks; 85L containers; Free spindle and Y training systems;
		Sicilia (Italy)	Caruso et al. (1999b)	1994	1	6	‘Flordaprince’ peach cultivar; Tatura training system; 1500 trees/ha
	Destructive measurements	IRTA facilities (Lleida)	Donated data* by IRTA Fruit Production Program	2010	6	15	‘Merril O’Henry’ peach cultivar; irrigated; GF305 and Franc rootstocks; Epsilon, Tatura, Vase, Palmette and central leader training systems; 520-1039 trees/ha

*data non published.

Table B.4. Detailed information for Nut trees biomass dataset.

Non-Citrus Type	Data source	Location	Reference	Sample date	Dataset size	Crop age (years)	Available culture traits information
Nuts	**Non-destructive Measurement** (trunk diameter measured at 30-40 cm from soil to top)	Mas Bover (Tarragona, Catalonia)	Donated data by IRTA Fruit Production Program	2007;2010-2015	284	4-13	'Belona', 'Constanti', ' D. Largueta', ' Francolí', 'Glorieta', 'Guara', 'Marcona', 'Mardia', 'Marinada', 'Masbovera', 'Nonpareil', 'Penta', 'Ramillete', 'Soleta', 'Tardona', 'Tarraco', 'Vairo', '155', '12-350', '13-531', '23-160', '23-173', '24-53', '26-258', '26-408', '27-103', '28-117', '29-147', '29-148', '29-168', '29-59', '30-143', '30-156', '30-297', '31-213', '31-82', '32-563', '33-1040', '33-1056', '33-1307' almond cultivars; 'GF-677' and 'Garnem' rootstock; irrigated; 238 trees/ha and vase training system
				1978-1984; 1986;1988;1989;1991	132	2-8;10;12;13;15	‘Colorada’;’Cristomorto’, ‘Desmayo Largueta’, ‘Ferragnes’, ‘Garrigues’, ‘Marcona’, ‘Peraleja’, ‘Primorsky’, ‘Ramillete’, ‘Tardive de la verdiere’, ‘Texas’ and ‘Tuono’ almond cultivars; ungrafted rootstock; irrigated; vase training System
				1978-1981; 1986;1988;1991	170	2-5; 10;12;13	‘Marcona’ and ‘ROF’ almond cultivars; ‘Almendro 45’, ‘Almendro 54’, ‘Ayerbe 5-36’, ‘Comun B’, ‘Cristomorto’, ‘Desmayo Largueta’, ‘Esperanza Forta’, ‘Fourcournne’, ‘Garrigues’, ‘GF-677’, ‘Marcona-185’, ‘Mas Regany’, ‘Mena d’en Musté’, ‘Mollar de la princesa’, ‘Mollar de Tarragona’, ‘Princess’, ‘ROF’, ‘Rufina Gruesa’, ‘Texas’ rootstocks; rainfed; 318 and 357 trees/ha and training system
				1989;1991;1992;1996;1997	245	3-6;9-11	‘A-258’, ‘Achaak’, ‘Alcano-5’, ‘Alcano-6’, ‘Alcano-7’, ‘Alicante’, ‘Anyvol’, ‘Belle d’Aurons’, ‘Benito’, ‘Biota’, ‘C-48’, ‘C-5’, ‘C-54’, ‘C-57’, ‘C-69’, ‘Caima’, ‘Cebas’, ‘Chocolatera’, ‘Corbera’, ‘Del Cid’, ‘Domingo Daurio’, ‘Drepanoto’, ‘El Progreso’, ‘Enxaneta’, ‘F. Barese’, ‘Ferragnes’, ‘Ferrastar’, ‘Francesa’, ‘Francolí’, ‘Glorieta’, ‘Haguiga’, ‘Horta-1’, ‘Horta-2’, ‘Isidro’, ‘Jasams-1’, ‘Jasams-2’, ‘LL. Maials’, ‘M. d’en Muste’, ‘M. Hilari’, ‘Marcona Fina’, ‘Marcona Fina 85’, ‘Marcona’, ‘Mas Bovera’, ‘Moragas’, ‘Nano’, ‘Navarret’, ‘Nov. Esperanza’, ‘Parque Sama’, ‘Peret’, ‘Pirrta’, ‘Retson’, ‘Rumbeta’, ‘S-225’,‘Tardaneta’, ‘Tarragones’, ‘Verd’, ‘Victorino’, ‘Villalba’, ‘Wawana’, ‘155’, ‘235’, ‘254’, ‘601’, ‘2-28’, ‘190-Gorki’, ‘4-665’, ’77 Tozeur 3’, ‘791 Kichinev’, ‘8-1’, ‘8-5’, ‘905(LH08)3’, ‘906(DYOH)2’, ‘9-352’, ‘948Berhaiew’, ‘9-96’ almond cultivars; ‘Garrigues’ rootstock; rainfed; 265 trees/ha and tradicional vase training system
				1978-1983	28	2-7	‘Marcona’ and ‘ROF’ almod cultivars; Peach, Plum, and GF-677 rootstocks; irrigated and 318 trees/ha
				1978-1983	42	2-7	‘Ardechoise T. 572’, ‘Bruantine T. 72’, ‘Carriset T. 579’, ‘Comun B T. 139’, ‘Mollar T. 555’, ‘Nonpareil T. 568’, ‘Planeta (Elche) T. 574’ almond cultivars; irrigated and 318 trees/ha
				2007;2010-2015	284	4-13	‘155’; ’12-350’; ‘13-531’; ’21-332’; ’21-333’; ’23-160’; ’23-173’; ’24-53’; ’26-258’; ’26-408’; ‘27-103’; ’28-105’; ’28-117’; ’29-143’; ’29-147’; ’29-148’; ’29-168’; ’29-59’; ‘30-143’; ’30-143’; ’30-156’; ’30-297’; ’31-213’; ’31-82’; ’32-563’; ’33-1040’; ’33-1056’; ‘33-1307’; ‘Belona’; ‘Constantí’; ‘Desmayo Largueta’; ‘Francolí’; ‘Glorieta’

Cont. Table B.4.

Non-Citrus Type	Data source	Location	Reference	Sample date	Dataset size	Crop age (years)	Available culture traits information
Nuts	**Non-destructive Measurement** (trunk diameter measured at 30-40 cm from soil to top)	Borges Blanques (Lleida, Catalonia)	Donated data by IRTA Fruit Production Program	2002-2014	78	2-14	'Ferragnes', 'Francolí', 'Glorieta', 'Guara, 'Lauranne' and 'Masbovera' almond cultivars; INRA GF-677 rootstock; regulated dèficit irrigation; 278 trees/ha and vase training system
				2002-2011	120	1-10	'Vairo', 'Constantí', 'Tarraco', 'Marinada', '22-78', '23-160', '13-525', '13-173', '12-350', '13-531', '21-332', '23-154' almond cultivars ; 'INRA GF-677' rootstock; regulated dèficit irrigation; 303 trees/ha and vase training system
				2000-2014	48	2-7	‘Belona’, ‘Constanti’, ‘Guara’, ‘Marinada’, ‘Marta’, ‘Soleta’, ‘Tarraco’, ‘Vairo’ almond cultivars; GF-677 rootstock; irrigated; 213 trees/ha and vase training System
				2011-2015	67	2-6	‘Marinada’ and ‘Vairo’ almond cultivars; GF-677 rootstock; irrigated; diferents tree densities (278-1000 trees/ha) and diferent training systems.
				2011-2015	90	1-5	‘Marinada’ and ‘Vairo’ almond cultivars; ‘Cadaman’, ‘Garnem’, ‘INRA GF-677’, ‘Ishtara’, ‘MB-1-37’, ‘MI x AM x GR’, ‘Miropac’, ‘Nanopac’, ‘PAC 9801’ and ‘Puebla de Soto’ rootstocks; irrigated; 444 trees/ha and vase training system
		Gandesa (Tarragona, Catalonia)	Donated data by IRTA Fruit Production Program	2007-2013	117	4-10	'Cambra', 'Constantí', 'Felisia', 'Francolí', 'Glorieta', 'Guara', 'Marinada', 'Marta', 'Masbovera', 'Tarraco', 'Vairo', 'Antoñeta', '12-350', '21-332', '23-160', '23-173', '26-408', '28-108' almond cultivars; ' INRA GF-677' rootstock; regulated dèficit irrigation; 303 trees/ha and vase training system
		Mas Valero (Tarragona, Catalonia)	Donated data by IRTA Fruit Production Program	1989-1993; 1995-2000	100	2-13	'Cristomorto', 'Ferragnes', 'A-200', 'A-205', 'A-230', 'B-53', 'VT-121' almond cultivars; 'Garrigues' rootstock; rainfed; 333 trees/ha and vase training system
				1991;1998	20	5;12	‘Anxaneta’, ‘Critomorto’, ‘Farragnes’, ‘Francolí’, ‘Garbi’, ‘Glorieta’, ‘Guara’, ‘Masbovera’, ‘Moncayo’, ‘Tarragonès’ almond cultivars; rainfed ; 333 trees/ha and vase training system
		Villalba dels Arcs (Tarragona)	Donated data by IRTA Fruit Production Program	2012	14	16	‘Masbovera’ and ‘Glorieta’ almond cultivars; ungrafted and ‘GF-677’ rootstocks; regulated dèficit irrigation; 204 trees/ha and traditional vase training system
				2012	21	16	‘Masbovera’, ‘Glorieta’, ‘Guara’, ‘Francoli’, ‘Lauranne’, ‘Ferragnes’, ‘Glorieta’, ‘Masbovera’, ungrafted and ‘GF-677’ rootstocks; regulated dèficit irrigation; 204 trees/ha and traditional vase training system
				2006-2009;2012	30	10-13;16	‘Masbovera’, ‘Francolí’, ‘Ferragnes’, ‘Glorieta’, ‘Lauranne’, ‘Guara’ almond cultivars; ungrafted ‘Atocha’ rootstock; ungrafted and ‘GF-677’ rootstocks; regulated dèficit irrigation; 204 trees/ha and traditional vase training system

Table B.5. Detailed information of official information used for up scaling.

Woody crop class	Territory Level	Source	Year	Source Owner	Information
Vineyard	Municipality	Vineyard Registry of Catalonia	2013	Department of Agriculture. Government of Catalonia	Plant density distribution Crop age distribution
Olive	Regional	ESYRCE[a]	2012	Department of Agriculture Government of Spain	Crop age distribution
	Municipality	SIGPAC[b]	2009	Department of Agriculture. Government of Catalonia	Plant density distribution[c]
Fruit trees (seed and stone fruit)	Municipality	Sweet fruit Registry of Catalonia	2013	Department of Agriculture. Government of Catalonia	Plant density distribution Crop age distribution Species distribution
Nuts	Regional	ESYRCE[d]	2005	Department of Agriculture Government of Spain	Crop age distribution
	Municipality	SIGPAC[b]	2009	Department of Agriculture. Government of Catalonia	Plant density distribution[c]
Citrus	Municipality	Sweet fruit Registry of Catalonia	2013	Department of Agriculture. Government of Catalonia	Plant density distribution Crop age distribution Species distribution

[a] Survey of areas and yields of crops. Analysis of olive orchards in Spain (ESYRCE, 2012)

[b] Common Agricultural Policy Geographic Information System

[c] Plant density was estimated intersecting two vector layers: one vector layer (points) representing georeferenced olives trees and another vector layer (polygon) representing olive grove plots (SIGPAC, 2009). 2009 was the last year when olives trees were georeferenced as points for the Catalan SIGPAC information.

dSurvey of areas and yields of crops. Analysis of nut fruit orchards (ESRYCE, 2005).

Table B.6. Equations performed in the study to estimate biomass (dry matter, DM) or biometric variables used as intermediate step to estimate biomass for each woody crop as a function of crop age. Number in brackets are standard error of the model coefficients.

Woody Crop	Type of Variable	Variable Name	Units	Formula	Coefficients		
					a	*b*	*c*
Nuts	Biometric	TD	cm	$TD = (-a/(1+e^{(b)})) + a/(1+ e^{(b+cAge)})$	132.528 (974.287)	0.494 (1.404)	-0.051 (0.378)
Grapevine	Biomass (DM)	ABGB	kg/vine	$ABGB= (-a/(1+e^{(b)})) + a/(1+ e^{(b+cAge)})$	5.196 (0.445)	2.269 (0.383)	-0.256 (0.416)
		BGB	kg/vine	$BGB= a\ (1- e^{(bAge)})$	4.927 (0.806)	-0.031 (0.008)	-
Olive	Biometric	TBA	cm^2	$TBA = a\ (1- e^{(bAge)})$	1033.253 (77.091)	-0.018 (0.002)	-
Seed Fruit	Biomass (DM)	ABGB	kg/tree	$ABGB= (-a/(1+e^{(b)})) + a/(1+ e^{(b+cAge)})$	34.794 (21.939)	1.482 (0.802)	-0.111 (0.084)
Stone Fruit	Biomass (DM)	ABGB	kg/tree	$ABGB= (-a/(1+e^{(b)})) + a/(1+ e^{(b+cAge)})$	54.382 (7.373)	2.572 (1.217)	-0.503 (0.246)
Citrus	Biomass (DM)	ABGB	kg/tree	$ABGB= (-a/(1+e^{(b)})) + a/(1+ e^{(b+cAge)})$	102.490 (11.539)	5.524 (1.212)	-0.574 (0.148)
		BGB	kg/tree	$ABGB= (-a/(1+e^{(b)})) + a/(1+ e^{(b+cAge)})$	37.424 (9.845)	3.616 (0.561)	-0.336 (0.093)

ABGB: Aboveground Biomass
BGB: Belowground Biomass
TD: Trunk Diameter (at 30-40 cm from ground)
TBA: Trunk Basal Area (at 30 cm from ground)

Table B.7. Annual carbon sequestration rates (Mg C/ha/year) for different crop age ranges (years) and crop type up to the age limit in fitted curves of biomass or biometrics variables performed in the present study.

		Crop Age Ranges (years)												
Crops	**Average***	**0-5**	**6-10**	**11-15**	**16-20**	**21-25**	**26-30**	**31-35**	**36-40**	**41-50**	**51-60**	**61-70**	**71-80**	**>80**
Vine	0.35	0.52	0.67	0.57	0.33	0.18	0.12	0.09	-	-	-	-	-	-
Olive	0.38	0.55	0.51	0.46	0.42	0.38	0.35	0.32	0.29	0.25	0.21	0.18	0.15	0.11
Nuts	2.25	0.80	2.39	3.97	-	-	-	-	-	-	-	-	-	-
Seed Fruit	1.68	1.41	1.73	1.92	1.83	1.51	-	-	-	-	-	-	-	-
Stone Fruit	1.84	4.65	4.33	0.72	-	-	-	-	-	-	-	-	-	-
Citrus	3.32	0.84	4.41	4.46	-	-	-	-	-	-	-	-	-	-

Average values of the first 50 years for Olive, 35 years for Vine, 26 years for seed fruit, 25 year for Stone fruit, 13 years for nuts and 14 years for citrus.

Table B.8. Land use transition matrix (ha) from 2013 (vertical, red) to 2019 (horizontal, yellow) derived from SIGPAC. Hectares in bold represent area with no land use change

			SIGPAC 2019										
		Land Use Class	Woddy Crop Association	Citrus	Forest	Nuts	Fruit Trees	Olive	Grassland	Arable Land	Vineyard	Urban & Others	**TOTAL 2013**
	Land Use Class	**Code**	1	2	3	4	5	6	7	8	9	10	
SIGPAC 2013	Woddy Crop Association	10	**1185**	2	27	26	11	76	64	83	45	62	**1581**
	Citrus	20	5	**8136**	11	88	107	145	91	496	3	269	**9351**
	Forest	30	16	5	**795296**	730	710	1832	44135	11932	1055	10072	**865783**
	Nuts	40	63	7	949	**42777**	750	2049	2121	4474	586	2020	**55796**
	Fruit Trees	50	187	113	920	2504	**66264**	1670	2500	9235	503	3002	**86898**
	Olive	60	118	90	2111	2364	1411	**105596**	5348	3818	777	3590	**125223**
	Grassland	70	61	30	36594	1734	1912	4260	**1038329**	28379	2697	21285	**1135281**
	Arable Land	80	44	109	9989	4216	6605	3077	34036	**473676**	5316	18751	**555819**
	Vineyard	90	28	NE	948	565	311	718	2329	3702	**44884**	2097	**55582**
	Urban & Others	100	54	41	8885	939	1528	1799	14556	12891	1682	**268642**	**311017**
		TOTAL 2019	**1761**	**8533**	**855730**	**55943**	**79609**	**121222**	**1143509**	**548686**	**57548**	**329790**	**3202331**

Table B.9. Accumulated percentage of crop area representing crop age defined in the fitted equations of biomass or biometric variables.

Crop	Age (years)	Crop Area (%)
Vineyard	less than 35	91.1
Olive	less than 104	91.5
Seed Fruit	less than 26	87.7
Stone Fruit	less than 15	85.5
Citrus	less than 14	55.4
Nuts	less than 13	22.0

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Chapter 2

Appendix C

Methodology Details

1. Details from datasets and measurements

1.1 Grapevine:

Details on procedure of non-destructive and destructive measurements

Non-destructive measurements were based in biometrics measurements (longitude and diameters of trunk and cordons) of the permanent aboveground biomass of vines (trunk and cordons). Leaves, berries and vine shoots are not considered as permanent biomass. Non-destructive measurements were carried out in vineyards located in IRTA-Torre Marimon facilities (41° 36' N 2° 10'E). We measured diameter and length of trunk and cordons and assuming cylindrical shape (constant diameter) and, based in these biometric variables, we estimate the volume of vine (Williams et al. 2011). To estimate biomass from volume, we multiplied volume by vine wood density (g/cm^3). Some pieces of vine wood from each cultivar were collected in the field. We measured the volume of these pieces of wood by the water displacement method (Picard et al. 2012), then we dried at 65 °C for 7 days and weighted. The averaged wood density value used was 0.51 g/cm^3 very close to values published in some studies (Munalula and Meincken 2009, Nasser et al. 2014). In addition, data from non-destructive were donated from other authors and included in the study (Dr. Gonzaga Santesteban, Universidad de Navarra). In this case, in order to estimate biomass from volume, we assume a wood density value of 0.75 g/cm^3, as average of the range of values published in literature: 0.50-0.80 g/cm^3 (Candolfi-Vasconcelos and Castagnoli 1998, Munalula and Meincken 2009, Nasser et al. 2014, Miranda et al. 2017).

Destructive measurements were carried out in IRTA-Torre Marimon facilities (41° 36' N 2° 10'E) and in a plot located in Penedès district (41° 20' N 1° 39' E) during the period 2006-2011. Aboveground was separated above the rootstock and dry at 65 °C for 7 days and weighted. Moreover, data from destructive and non-destructive measurements donated from other authors were included in the study in the case of vines (Dr. Gonzaga Santesteban, Universidad de Navarra). Table B.1 in Appendix B describes all the data used to build the function biomass-age in the case of vines coming from areas under Mediterranean conditions (Fig. A.1 in Appendix A).

Belowground biomass of vines (belonging to the destructive measurements carried out in Barcelona (Table B.1 of Appendix B) was collected by excavating 1x1 m at 1 m depth, and dry at 65°C for 7 days and weighted. Root biomass from destructive measurements of vines from 1 to 35 years were dried at 65°C for 7 days and weighted.

1.2 Olive:

Details on measurements and data homogenization

TBA data was measured to 30 cm from ground. Some TBA data from literature was measured to a different height from ground (from 20 cm to 60 cm), so we homogenized data to 30 cm applying a correction factors (based on olive trunk shape) supposing olive trunk shape as a truncated cone. Trunk shape was modeled from own measures to different height from the ground (data not shown) performed in Torre Marimon Olive grove, NE Spain. Detailed information in Table B.2 in Appendix B.

Root: shoot ratios review

Regarding root:shoot ratios for olive some values have found in literature. In orchards and for evergreen species Montanaro et al. (2008) and Liguori et al. (2009) observed that annual C partitioned to the roots was 30% of the total fixed one. Almagro et al. (2010) established a R:S ratio of 0.21 in 100 years aged olive trees in SE Spain by using the core method to estimate belowground biomass. Sofo et al. (2005) reported for a young olive plantation a belowground biomass allocation of 27%, Palese et al. (2013) estimated root biomass as 50% of the annual biomass production of olive trees following Cannell (1985) for a conventional and sustainable system in southern Italy, and Bustan et al. (2011) estimated olive root biomass as 25% of the aboveground perennial mass using relevant data from Bouat (1987) and Erel (2009).

1.3 Fruit trees:

Details non-destructive and destructive measurements

Non-destructive measurements were carried out only for pomes trees in IRTA-Mas Badia experimental station facilities. We measured length and diameter from different segments of the tree established by being similar to cylindrical shape (Picard et al. 2012). Pruning material was not considered. To estimate biomass from volume, we multiplied volume by apple wood density (g/cm^3). Some pieces of apple tree wood from 3 different cultivars were collected in the field aiming to obtain an average value of wood density following the same methodology described above for vines. The averaged wood density value used was 0.58 g/cm^3, not so far from values published in literature for different fruit trees that range between 0.66-0.76 g/cm^3 (Passialis and Grigoriou 1999).

Destructive measurements were carried out experimental plots of apple, pear and peach trees located in IRTA experimental station from Lleida. This data were donated from the Fruit Production IRTA Program. Aboveground was separated from the rootstock and dry at 65 °C for 7 days and weighted.

2. Literature review of carbon content

In vines, Munalula and Meincken (2009) published a C content value for vine biomass of 43.7%, Downton and Grant (1992) a value of 43.4% for grapevine and Greer and Sicard (2009) a value of 45%. A C content value of 50% of dry weight was assumed by Sofo et al. (2003) for olive biomass and 48% by Palese et al. (2013) for olives trees following Robin (1997) and as some other authors (Sofo et al. 2005, Xiloyannis et al. 2007, Almagro et al. 2010, Nardino et al. 2013). Montero et al. (2005) published a value of 47.3% for Olea europea sylvestris. For fruit trees, values from 45.3% to 47.5% of C content in biomass for peach was proposed by Grossman and Dejong (1994) and Morhart et al. (2016) published values 47.8% for wild cherry. The C content for citrus range from 44% to 46% of biomass (Liguori et al. 2009, Iglesias et al. 2013, Quiñones et al. 2013).

3. Details of scaling up performance

The availability of this official information at this level was a limiting factor for some of the woody crop classes studied. For example, it was difficult to obtain information about olives or nut trees age distribution because of the lack of a specific registry for these crops. However, plant density data for olive and nut trees was more accurately estimated because 2009 was the last year SIGPAC in Catalonia geographically referenced these crops (olives and nut trees) at tree level. In both cases, plant density was calculated intersecting the olive or nuts plots polygons with the layer of olive or nut trees and a plant density distribution was estimated for each municipality.

Distribution of area for the different woody crop classes is based in SIGPAC (2013). The Agricultural Plots Geographical Information System (SIGPAC, acronym in Spanish) was created by the Agriculture Ministry of Spain (through FEGA; acronym in Spanish of Spanish Agrarian Guarantee Fund) and each of the Spanish regional governments (through Councils of Agriculture) in order to facilitate farmers the submissions of applications to agricultural subsidies from CAP (Common Agriculture Policy). SIGPAC is based in aerial and spatial orthoimagery and the national land registry (Cadastral survey) and it has been updated yearly from 2005.

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Chapter 3

Appendix A

Supporting Material and Methods, Results and Discussion

Figures

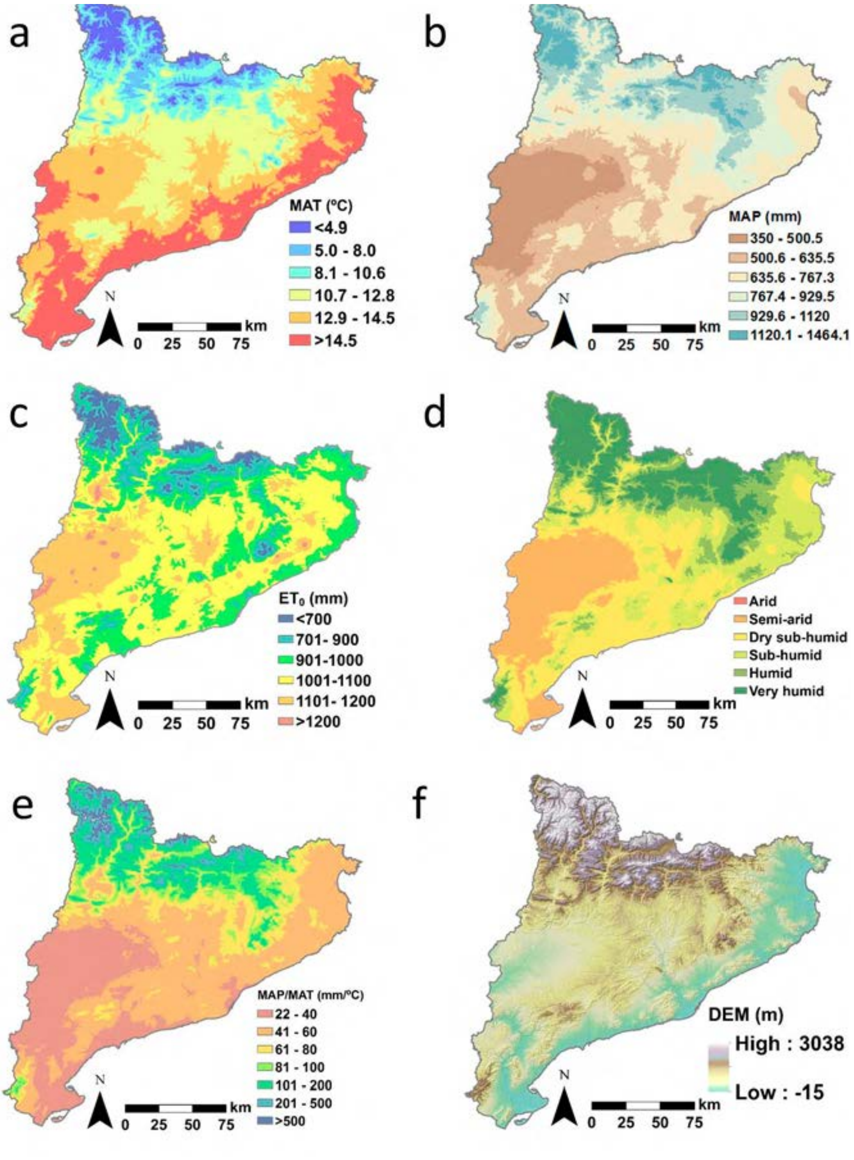


Figure A.1. Spatial distribution of environmental variables (climate and topography): a) mean annual temperature (MAT, ºC); b) mean annual precipitation (MAP, mm); c) mean annual evapotranspiration (ET_0, mm); d) aridity index (AI, dimensionless); e) MAP/MAT (mm/ºC) ratio and f) altitude in meters above sea level (Digital Elevation model, DEM) of the study area.

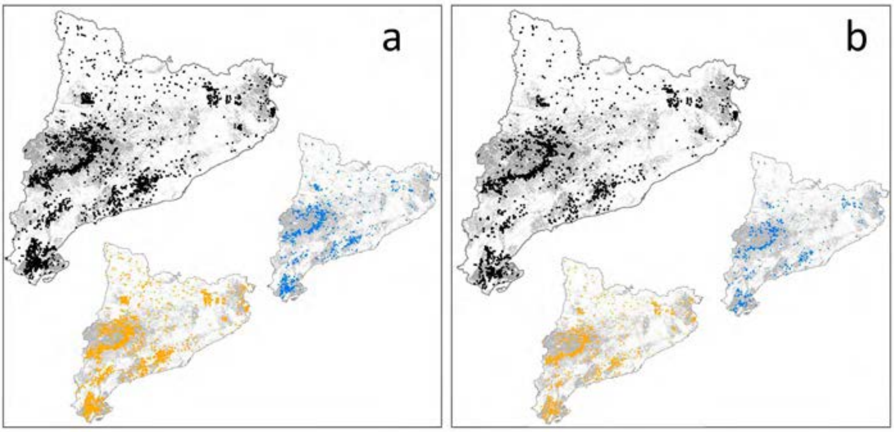


Figure A.2. Spatial distribution of soil profiles (represented as black dots) in crop areas of Catalonia for each data set: a) 0-30 cm depth interval data set (2816 profiles) and b) 30-100 cm depth interval dataset (1612 profiles). Grey shadows represent agriculture spatial distribution. Blue dots represent spatial distribution of test profiles (722 profiles in a and 393 in b) and orange dots represents training profiles using in modelling (2094 profiles in a and 1219 profiles in b).

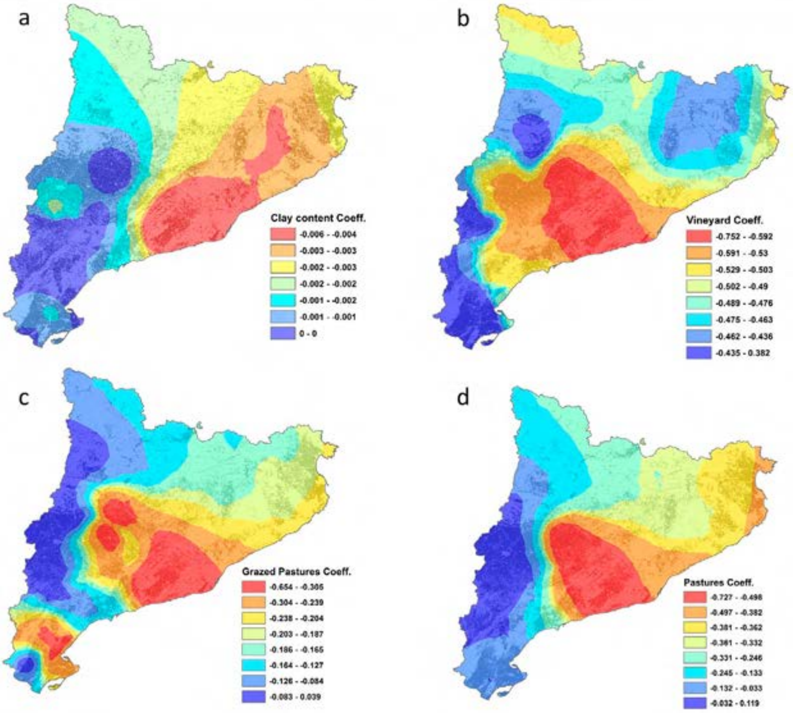


Figure A.3. Spatial distribution of GWR coefficients (kriged) from explanatory variables of square-root SOC stock at 0-30 cm depth interval: a) Clay content, b) Vineyard, c) Grazed pastures and d) Pastures. Shadows under colors showing spatial distribution of GWR coefficients represent the spatial distribution of the Catalan agriculture. Darker shadows under colors represent spatial distribution of the category in question. Agricultural land use categories coefficients refer Rice (SOC stock mean Value).

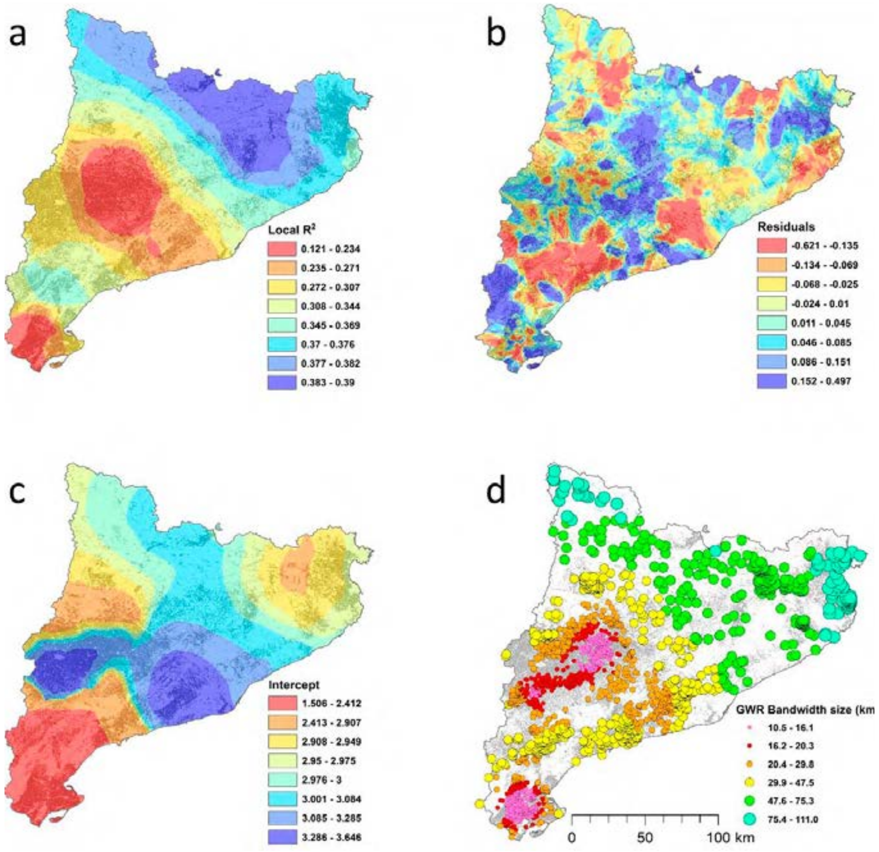


Figure A.4. Spatial distribution of: a) local R^2, b) residuals, c) intercept and d) bandwidth size of GWR model (square-root SOC stock) at 0-30 cm depth interval. Shadows under colors showing spatial distribution of GWR coefficients represent the spatial distribution of the Catalan agriculture.

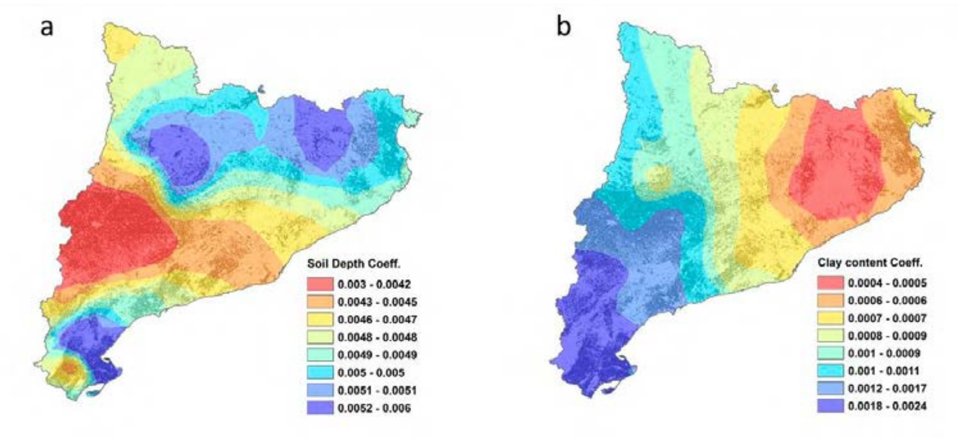
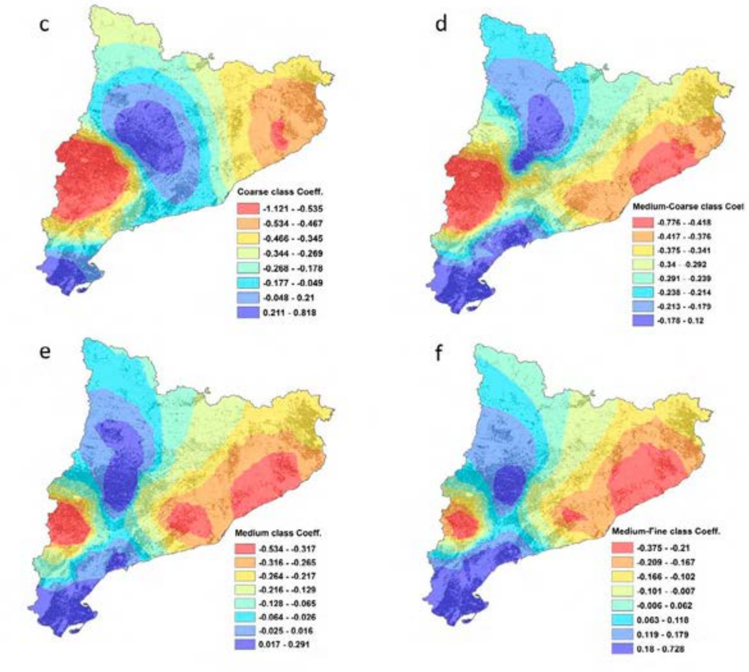


Figure A.5. Spatial distribution of GWR coefficients (kriged) from explanatory variables of square-root SOC stock at 30-100 cm depth interval: a) Soil depth and b) Clay content. Shadows under colors showing spatial distribution of GWR coefficients represent the spatial distribution of the Catalan agriculture.



Cont. Fig. A.5. Spatial distribution of GWR coefficients (kriged) from explanatory variables of square-root SOC stock at 30-100 cm depth interval: c) Coarse texture class, d) Medium-Coarse texture class, e) Medium texture class and f) Medium-Fine texture class. Shadows under colors showing spatial distribution of GWR coefficients represent the spatial distribution of the Catalan agriculture. Texture class categories refer Fine texture class. Colors are not representing the same interval coefficients in each texture class map.

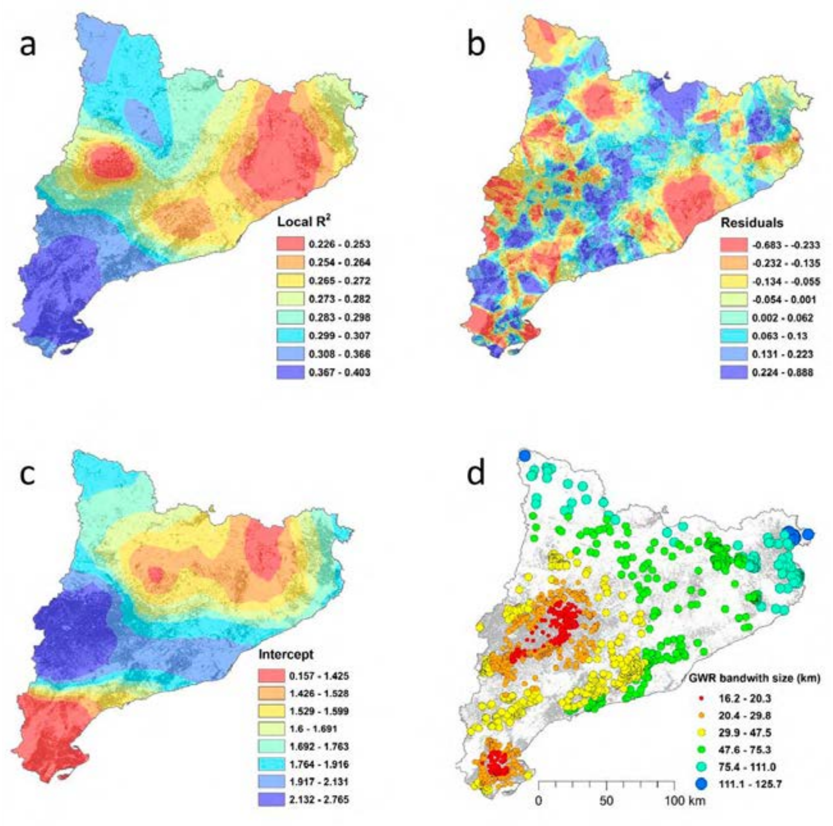


Figure A.6. Spatial distribution of: a) local R^2, b) residuals, c) intercept and d) bandwidth size of GWR model (square-root SOC stock) at 30-100 cm depth interval. Shadows under colors showing spatial distribution of GWR coefficients represent the spatial distribution of the Catalan agriculture.

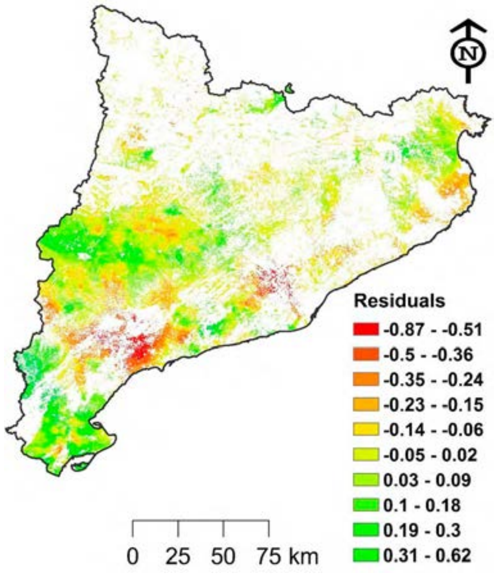


Figure A.7. Spatial distribution of kriged residuals (square-root transformed SOC stock) of GLS model at 0-30 cm. The areas rendered with white color are non-agricultural areas.

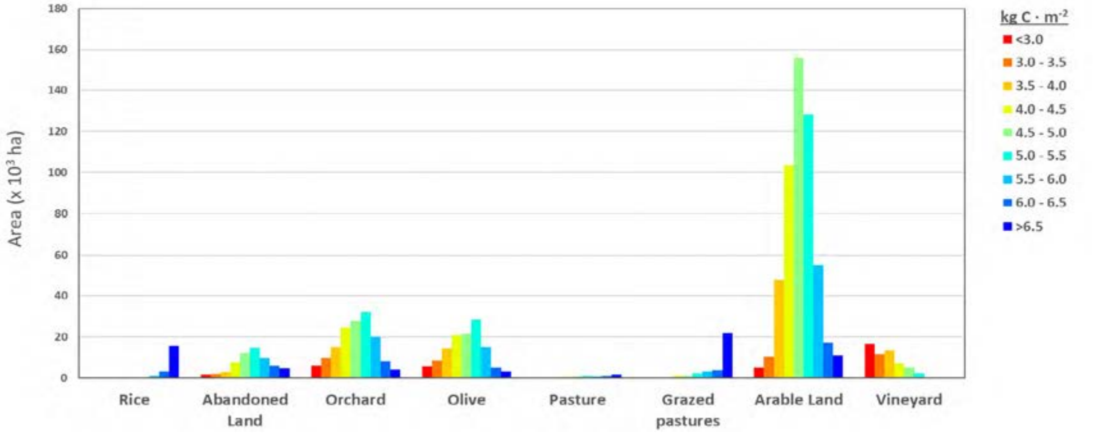


Figure A.8. Distribution of SOC stocks (0-30 cm) for the study area based on the digital mapping aggregated by agricultural land use.

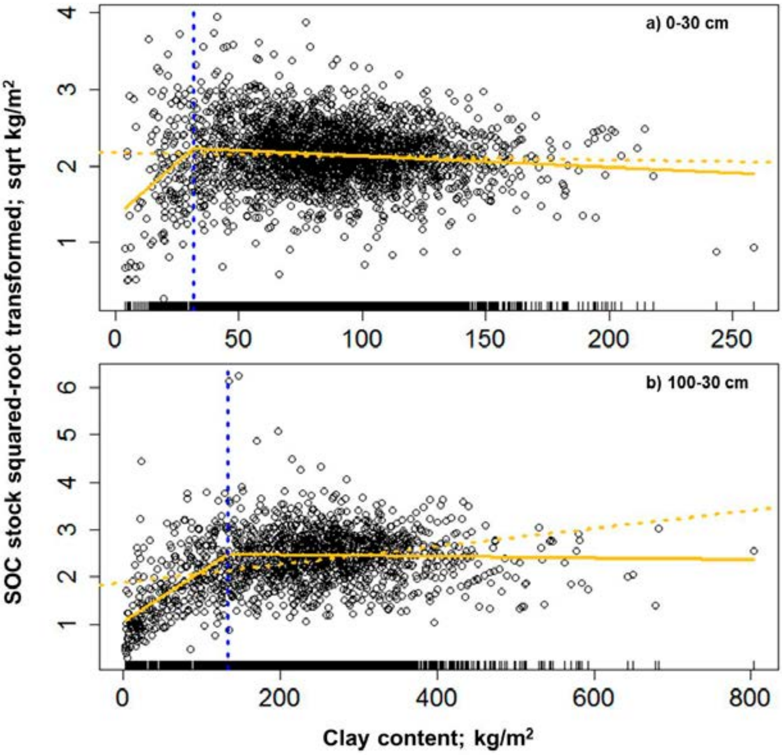
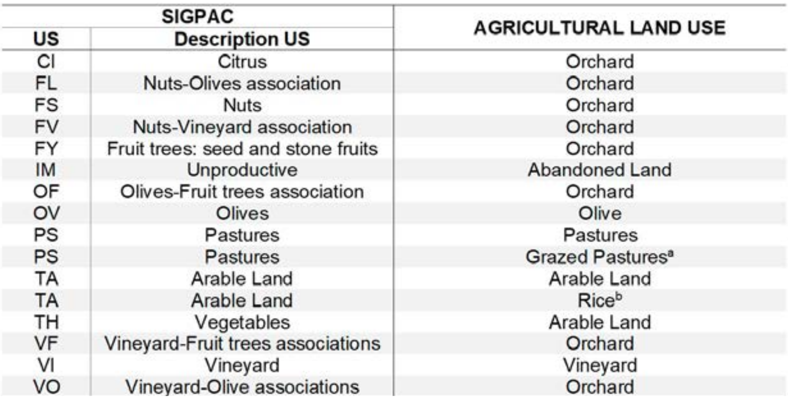


Figure A.9. Soil organic carbon (SOC) stocks square-root transformed (sqrt kg/m^2) against clay content (kg/m^2) estimated from both depth intervals: (a) 0-30 cm and (b) 30-100 cm for 2816, 1612 profiles, respectively, in agricultural soils of Catalonia. Circles are the estimated data (SOC and clay stocks), blue vertical dash lines are the inflection points and yellow solid lines are the segmented regression applied to below and above the inflection point. Yellow dash lines are the regression applied to total data. Marks inside the x-axis show density of estimated data.

Tables

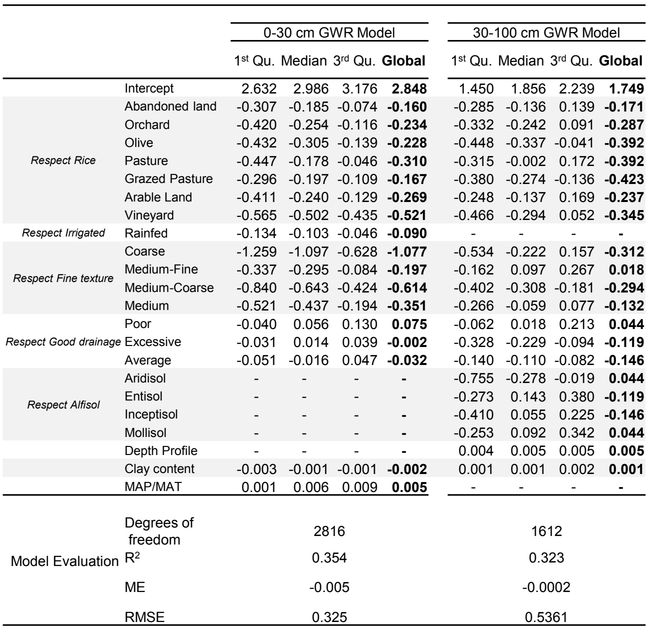
Table A.1. Reclass of the explanatory variable "Agricultural Land Use" based on SIGPAC "US" attribute.



SIGPAC		AGRICULTURAL LAND USE
US	**Description US**	
CI	Citrus	Orchard
FL	Nuts-Olives association	Orchard
FS	Nuts	Orchard
FV	Nuts-Vineyard association	Orchard
FY	Fruit trees: seed and stone fruits	Orchard
IM	Unproductive	Abandoned Land
OF	Olives-Fruit trees association	Orchard
OV	Olives	Olive
PS	Pastures	Pastures
PS	Pastures	Grazed Pastures[a]
TA	Arable Land	Arable Land
TA	Arable Land	Rice[b]
TH	Vegetables	Arable Land
VF	Vineyard-Fruit trees associations	Orchard
VI	Vineyard	Vineyard
VO	Vineyard-Olive associations	Orchard

[a] Grazed pastures are represented as PS category in SIGPAC with the attribute CA (grazing admissibility coefficient) > 60, most likely to be grazed. CA attribute of SIGPAC depends on variables as slope or type of vegetation. [b] Rice surface were extracted from DUN (2016) and subtracted from the "US" SIGPAC category TA.

Table A.2. GWR model coefficients of square-root transformed SOC (sqrt kg/m^2) and validation statistics (based on total data set) corresponding to 0-30 cm and 30-100 cm depth intervals.



		0-30 cm GWR Model				30-100 cm GWR Model			
		1st Qu.	Median	3rd Qu.	**Global**	1st Qu.	Median	3rd Qu.	**Global**
	Intercept	2.632	2.986	3.176	**2.848**	1.450	1.856	2.239	**1.749**
Respect Rice	Abandoned land	-0.307	-0.185	-0.074	**-0.160**	-0.285	-0.136	0.139	**-0.171**
	Orchard	-0.420	-0.254	-0.116	**-0.234**	-0.332	-0.242	0.091	**-0.287**
	Olive	-0.432	-0.305	-0.139	**-0.228**	-0.448	-0.337	-0.041	**-0.392**
	Pasture	-0.447	-0.178	-0.046	**-0.310**	-0.315	-0.002	0.172	**-0.392**
	Grazed Pasture	-0.296	-0.197	-0.109	**-0.167**	-0.380	-0.274	-0.136	**-0.423**
	Arable Land	-0.411	-0.240	-0.129	**-0.269**	-0.248	-0.137	0.169	**-0.237**
	Vineyard	-0.565	-0.502	-0.435	**-0.521**	-0.466	-0.294	0.052	**-0.345**
Respect Irrigated	Rainfed	-0.134	-0.103	-0.046	**-0.090**	-	-	-	**-**
Respect Fine texture	Coarse	-1.259	-1.097	-0.628	**-1.077**	-0.534	-0.222	0.157	**-0.312**
	Medium-Fine	-0.337	-0.295	-0.084	**-0.197**	-0.162	0.097	0.267	**0.018**
	Medium-Coarse	-0.840	-0.643	-0.424	**-0.614**	-0.402	-0.308	-0.181	**-0.294**
	Medium	-0.521	-0.437	-0.194	**-0.351**	-0.266	-0.059	0.077	**-0.132**
Respect Good drainage	Poor	-0.040	0.056	0.130	**0.075**	-0.062	0.018	0.213	**0.044**
	Excessive	-0.031	0.014	0.039	**-0.002**	-0.328	-0.229	-0.094	**-0.119**
	Average	-0.051	-0.016	0.047	**-0.032**	-0.140	-0.110	-0.082	**-0.146**
Respect Alfisol	Aridisol	-	-	-	**-**	-0.755	-0.278	-0.019	**0.044**
	Entisol	-	-	-	**-**	-0.273	0.143	0.380	**-0.119**
	Inceptisol	-	-	-	**-**	-0.410	0.055	0.225	**-0.146**
	Mollisol	-	-	-	**-**	-0.253	0.092	0.342	**0.044**
	Depth Profile	-	-	-	**-**	0.004	0.005	0.005	**0.005**
	Clay content	-0.003	-0.001	-0.001	**-0.002**	0.001	0.001	0.002	**0.001**
	MAP/MAT	0.001	0.006	0.009	**0.005**	-	-	-	**-**
Model Evaluation	Degrees of freedom	2816				1612			
	R^2	0.354				0.323			
	ME	-0.005				-0.0002			
	RMSE	0.325				0.5361			

Reference variables for each categorical predictor is denoted at the left side followed by the word "Respect". Global coefficients are shown in bold. Coefficients of variables excluded for each model in the backward stepwise performance are marked with a hyphen.

Table A.3. GLSmap model-averaged coefficients, standard error, (SE), t-value and significance for each variable (based on full topsoil data set: 2816 profiles) for SOC stock (square-root transformed) in the 0-30 cm depth interval. Triple-asterisk “***” denotes p<0.001.

	GLS (0-30 cm)		
	Coefficients ± SE	t value	
Intercept	2.351 ± 0.056	41.827	***
Abandoned land	-0.271 ± 0.060	-4.524	***
Orchard	-0.362 ± 0.057	-6.348	***
Olive	-0.354 ± 0.059	-5.972	***
Pasture	-0.498 ± 0.082	-6.065	***
Grazed Pasture	-0.296 ± 0.071	-4.152	***
Arable Land	-0.408 ± 0.056	-7.296	***
Vineyard	-0.663 ± 0.061	-10.972	***
Rainfed	-0.109 ± 0.022	-5.068	***
Aridity Index	0.355 ± 0.046	7.735	***
Altitude	0.0003 ± 0.000004	7.329	***

*Model formula (including GLS model coefficients) for mapping agricultural topsoil SOC stocks is: **sqrt (SOC 0-30 cm) ~ 2.351 + AbL* -0.271 + OR * -0.362 + OV * -0.354 + PA * -0.498 + GP * -0.296 + ArL*-0.408 + VI * -0.663 + Ra * -0.109 + AI * 0.355 + At * 0.0003**, where variables are represented as: AbL (abandoned land), OR (orchard), OV (olive), PA (pasture), GP (grazed pasture), ArL (arable land), VI (vineyard), RA (rainfed), AI (aridity index) and At (altitude). Agricultural categories will take 0 or 1 values indicating absence or presence of categories. Irrigated and rice are reference categories for both agricultural predictors.

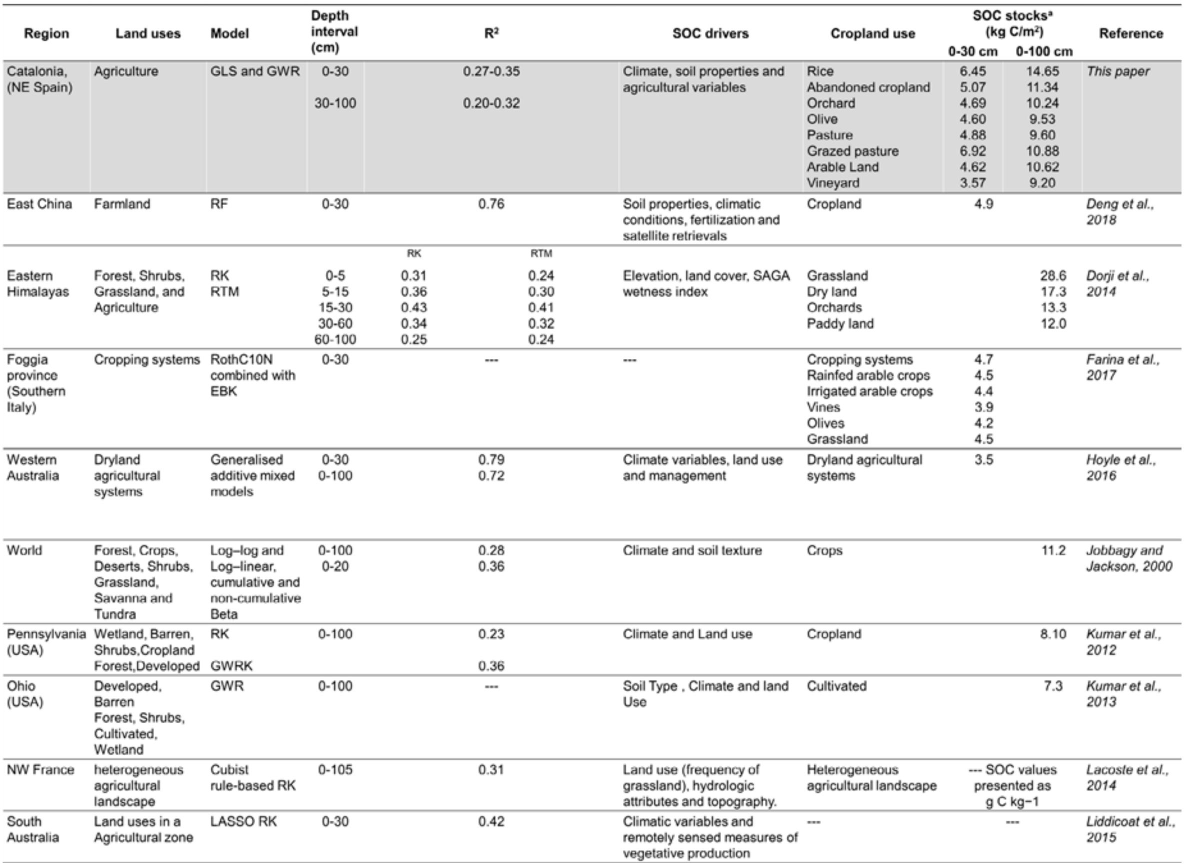
Table A.4. Summary of relevant information from some of the references regarding modelling SOC, important SOC drivers and agricultural SOC stocks mean values.

Region	Land uses	Model	Depth interval (cm)	R^2			SOC drivers	Cropland use	SOC stocks^a (kg C/m^2)		Reference
									0-30 cm	0-100 cm	
Catalonia, (NE Spain)	Agriculture	GLS and GWR	0-30 30-100	0.27-0.35 0.20-0.32			Climate, soil properties and agricultural variables	Rice Abandoned cropland Orchard Olive Pasture Grazed pasture Arable Land Vineyard	6.45 5.07 4.69 4.60 4.88 6.92 4.62 3.57	14.65 11.34 10.24 9.53 9.60 10.88 10.62 9.20	*This paper*
Denmark	Forest, Seminatural areas, Artificial Surface, Agriculture and Wetlands	RK	0-5 5-15 15-30 30-60 60-100	0.41 0.42 0.43 0.29 0.23			Precipitation, Land use, Soil type, Wetland, Elevation, Wetness index and multi-resolution index of valley bottom flatness.	Agriculture		12.1	*Adhikari et al., 2014*
				LUCAS	LUCAS+CZOs	LUCAS+CZOs+ BIOSOIL					
Europe	Cropland, Pastures, Forests, Scrub/herbaceous vegetation and Open Spaces	RK using 3 combinations of databases	0-30	0.40	0.41	0.33	Elevation, Slope, Compound topographic index, Temperature, Precipitation, Texture, Soil type and Land use.	Arable Land Permanent crops Pastures Heterogeneous agric. areas	--- SOC values presented as %		*Aksoy et al., 2016*
Nigeria	Forest, Shrubland, Savanna, Grassland and Cropland	RF, Cubist and BRT		RF	Cubist	BRT	Soil type, climate, vegetation indices and terrain attributes	Cropland		6.94	*Akpa et al., 2016*
			0-5 5-15 15-30 30-60 60-100	0.34 0.30 0.20 0.20 0.18	0.32 0.26 0.16 0.13 0.11	0.25 0.20 0.11 0.09 0.07					
Murcia (SE Spain)	Forestland Shrubland Cropland	Stepwise multiple regression analysis		Forestland	Shrubland	Cropland	Climatic factors, textural factors, land use, soil type and lithology. Topsoil: climatic factors Subsoil: textural factors and lithology	Cropland		6.3	*Albaladejo et al., 2013*
			0-20 20-40 40-60 60-100	0.15 0. 12 0.40 0.45	0.36 0.39 0.10 0.33	0.21 0.16 0.18 0.11					
NE Spain	Forest, Grassland-pasture and Agriculture	Century model	0-30	---			---	Grape-olive, Rain-fed arable land under continuous annual cropping and No-tillage and orchard.	> 6.5		*Alvaro-Fuentes et al., 2011*
Andalucia (South Spain)	Not specified	RF and MLR		RF		MLR	Precipitation, Enhanced Vegetation Index, Multiresolution Valley Bottom Flatness Index and Topography	---	--- SOC values presented as %		*Armas et al., 2017*
			0-5 5-15 15-30 30-60 60-100 100-200	0.62 0.63 0.63 0.63 0.61 0.62		0.5 0.27 0.16 0.12 0.28 0.05					
S.W. Iran	Cropland and natural vegetation	ANN RT		ANN		RT	Covariates derived from the Imagery and DEM	Irrigated farming Dry farming Orchards		~6* ~4* ~7*	*Chakan et al., 2017*
			0-5 5-15 15-30 30-60 60-100	0.62 0.59 0.66 0.61 0.55		0.53 0.50 0.46 0.53 0.43					
France	Cropland Vineyard/orchard Forest Grassland Others	RK	0-30 30-50	0.47			Land cover, Parent material, NPP, MAP and MAT	Cropland Vineyard/orchard Forest Grassland Others	4.58 3.17 6.62 6.63 6.08		*Chen et al., 2018*
Italy	Cropland	---	0-30	---			---	Arable land Agroforestry Vineyards Olive groves Orchards Rice fields	5.31 4.89 4.19 5.15 4.41 6.33		*Chiti et al., 2012*
Europe	Bareland, cropland, Grassland, shrub, wetlands and woodlands	GAM	0-20	0.27			--	Cropland	--- SOC values presented as g C kg−1		*De Brogniez et al., 2014*

Model name abbreviation: Regression kriging (RK), Random Forest (RF), Multiple Linear Regression (MLR), Geographically weighted regression kriging (GWRK), Geographically weighted regression (GWR), Empirical Bayesian Kriging (EBK), Generalized Additive Models (GAM), Least absolute shrinkage and selection operator (LASSO).

*interpreted value from a graph. a In order to be able to make comparisons with our results, some values were converted to kg C/m^2 from Mg C/ha (1 Mg C/ha is equivalent to 0.1 kg C/m^2).

Cont. Table A.4. Summary of relevant information from some of the references regarding modelling SOC, important SOC drivers and agricultural SOC stocks mean values.



Region	Land uses	Model	Depth interval (cm)	R²		SOC drivers	Cropland use	SOC stocks^a (kg C/m^2)		Reference
								0-30 cm	0-100 cm	
Catalonia, (NE Spain)	Agriculture	GLS and GWR	0-30	0.27-0.35		Climate, soil properties and agricultural variables	Rice	6.45	14.65	*This paper*
							Abandoned cropland	5.07	11.34	
			30-100	0.20-0.32			Orchard	4.69	10.24	
							Olive	4.60	9.53	
							Pasture	4.88	9.60	
							Grazed pasture	6.92	10.88	
							Arable Land	4.62	10.62	
							Vineyard	3.57	9.20	
East China	Farmland	RF	0-30	0.76		Soil properties, climatic conditions, fertilization and satellite retrievals	Cropland	4.9		*Deng et al., 2018*
				RK	RTM					
Eastern Himalayas	Forest, Shrubs, Grassland, and Agriculture	RK RTM	0-5	0.31	0.24	Elevation, land cover, SAGA wetness index	Grassland		28.6	*Dorji et al., 2014*
			5-15	0.36	0.30		Dry land		17.3	
			15-30	0.43	0.41		Orchards		13.3	
			30-60	0.34	0.32		Paddy land		12.0	
			60-100	0.25	0.24					
Foggia province (Southern Italy)	Cropping systems	RothC10N combined with EBK	0-30	---		---	Cropping systems	4.7		*Farina et al., 2017*
							Rainfed arable crops	4.5		
							Irrigated arable crops	4.4		
							Vines	3.9		
							Olives	4.2		
							Grassland	4.5		
Western Australia	Dryland agricultural systems	Generalised additive mixed models	0-30 0-100	0.79 0.72		Climate variables, land use and management	Dryland agricultural systems	3.5		*Hoyle et al., 2016*
World	Forest, Crops, Deserts, Shrubs, Grassland, Savanna and Tundra	Log–log and Log–linear, cumulative and non-cumulative Beta	0-100 0-20	0.28 0.36		Climate and soil texture	Crops		11.2	*Jobbagy and Jackson, 2000*
Pennsylvania (USA)	Wetland, Barren, Shrubs,Cropland Forest,Developed	RK GWRK	0-100	0.23 0.36		Climate and Land use	Cropland		8.10	*Kumar et al., 2012*
Ohio (USA)	Developed, Barren Forest, Shrubs, Cultivated, Wetland	GWR	0-100	---		Soil Type , Climate and land Use	Cultivated		7.3	*Kumar et al., 2013*
NW France	heterogeneous agricultural landscape	Cubist rule-based RK	0-105	0.31		Land use (frequency of grassland), hydrologic attributes and topography.	Heterogeneous agricultural landscape	--- SOC values presented as g C kg−1		*Lacoste et al., 2014*
South Australia	Land uses in a Agricultural zone	LASSO RK	0-30	0.42		Climatic variables and remotely sensed measures of vegetative production	---	---		*Liddicoat et al., 2015*

Model name abbreviation: Random Forest (RF), Multiple Linear Regression (MLR), Geographically Weighted Regression (GWR), Boosted Regression Tree (BRT), Structural Equation Modeling (SEM). *interpreted value from a graph. ^{a} In order to be able to make comparisons with our results, some values were converted to kg C/m^2 from Mg C/ha (1 Mg C/ha is equivalent to 0.1 kg C/m^2).

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Chapter 3

Appendix B

Methodology details

Explanatory variables and data sources

Climatic and topographic variables were obtained by overlaying each profile to a digital mapping.

Climatic variables were obtained from the Digital Climatic Atlas of Catalonia (Ninyerola et al., 2000). Mean annual temperature (MAT, °C) and mean total annual precipitation (MAP, mm) were obtained using a pixel size 180 m by 180 m. The mean annual potential evapotranspiration (ET_0, mm) was estimated following Hargreaves and Samani (1985) using the same pixel size. The MAP/MAT ratio (mm/°C) and the Aridity Index (AI, no units) understood as the ratio MAP/ET_0 (no units; Sahin, 2012) were used as climatic candidate variables as well.

Altitude (m) was sourced by overlaying each profile location directly to the digital elevation model (DEM) of Catalonia with spatial resolution 30×30 m (ICC, 2012). Spatial distribution of climatic variables and altitude over the study area are shown in maps from a to f in Figure A.2.

Agricultural variables considered followed DUN (Declaration of eligible agricultural area for EU's common agricultural policy payments, Catalonian Government) and SIGPAC categories (see in Table A.1 the reclassified agriculture land uses). Agriculture-related information coming from the original soil database were missing in some of the profiles and had to be estimated based on different sources according to the sampling year. Sources for estimating agricultural variables are: i) two editions of the map of crops and land uses (MCA, acronym in Spanish); ii) the Agricultural Plots Geographical Information System (SIGPAC, acronym in Spanish) from the year 2007 to 2016 and iii) historical ortophotos (ICGC). Agricultural variables are two: agricultural land use (eight categories: rice, abandoned cropland, orchard, olive, pasture, grazed pasture, arable land and vineyard) and water regime (two categories: irrigated and rainfed).

Soil properties came from the original soil database. Categorical soil variables coming from the original profiles data were reclassified in order to simplify categories and make statistical analysis and modelling easier. These categorical variables were: Profile Drainage (four categories: poor, excessive, average and good), Profile Textural class (five categories: fine, medium-fine, medium, mediuem-coarse and coarse) and Soil Type (five categories: Mollisol, Aridisol, Entisol, Inceptisol and Alfisol) following USDA Soil Taxonomy (SSS, 2014). Continuous soil variables were Depth profile (cm) understood as depth to rock, and Clay content (kg/m^2). As well as SOC estimations, clay content (estimated kg/m^2 from %) were calculated to each specific depth interval using the same methodology.

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Chapter 4

Appendix A

Supporting Material and Methods and Results

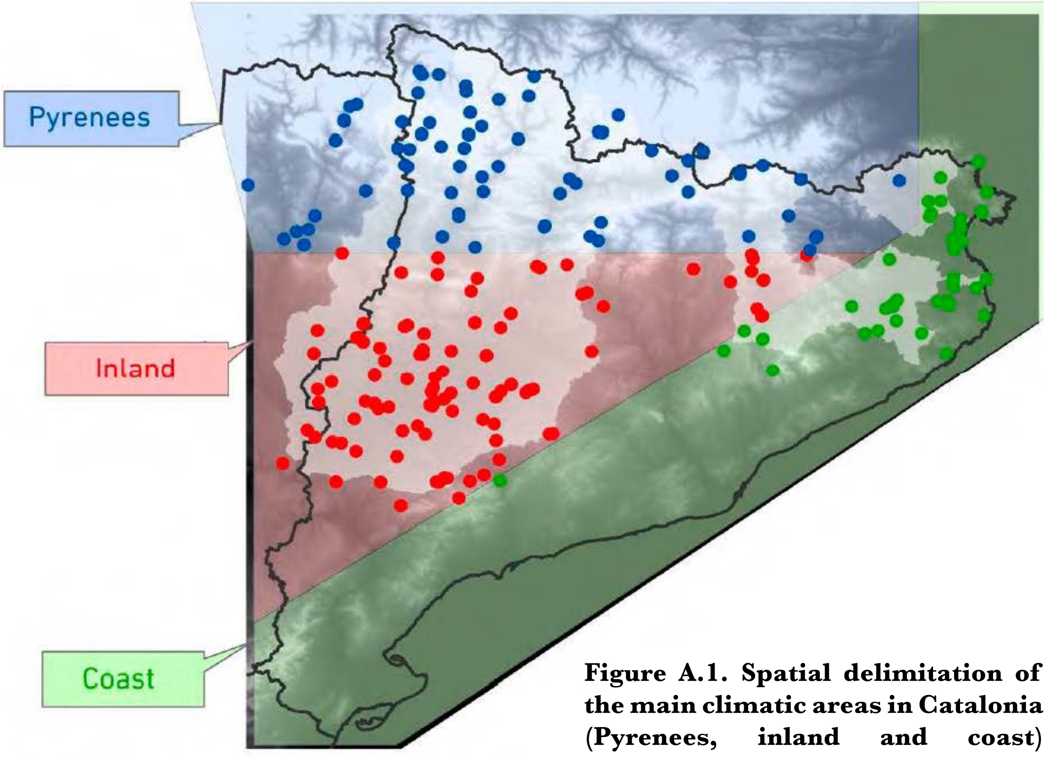

Figure A.1. Spatial delimitation of the main climatic areas in Catalonia (Pyrenees, inland and coast) represented by different colours and spatial distribution of the meteorological stations considered to assess the case-study basins (white shades). Figure from Pascual et al. (2016).

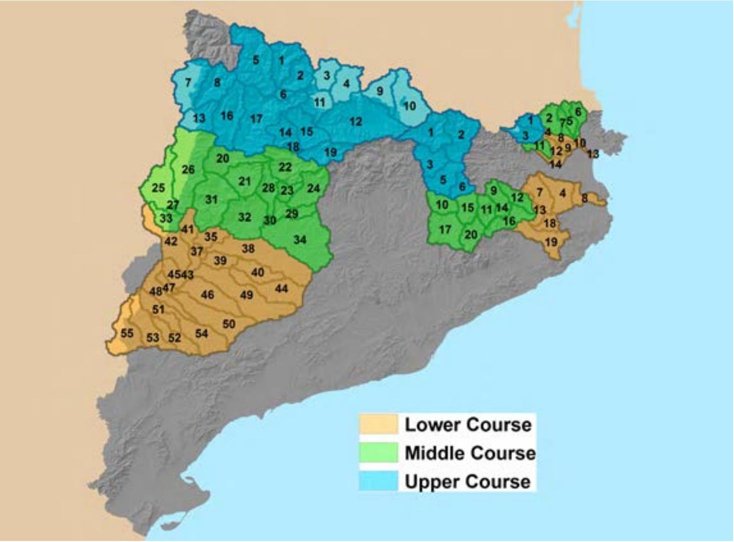

Figure A.2. Delineation of lower, middle and upper segments and subbasins of the case-study basins.

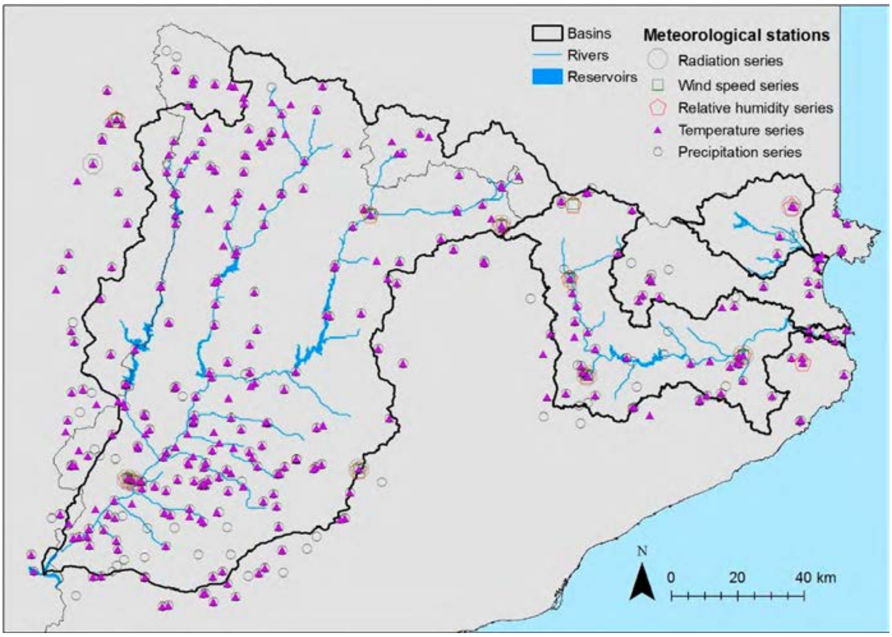

Figure A.3. Location of meteorological stations used in the hydrological modelling. Figure from Pascual et al. (2016).

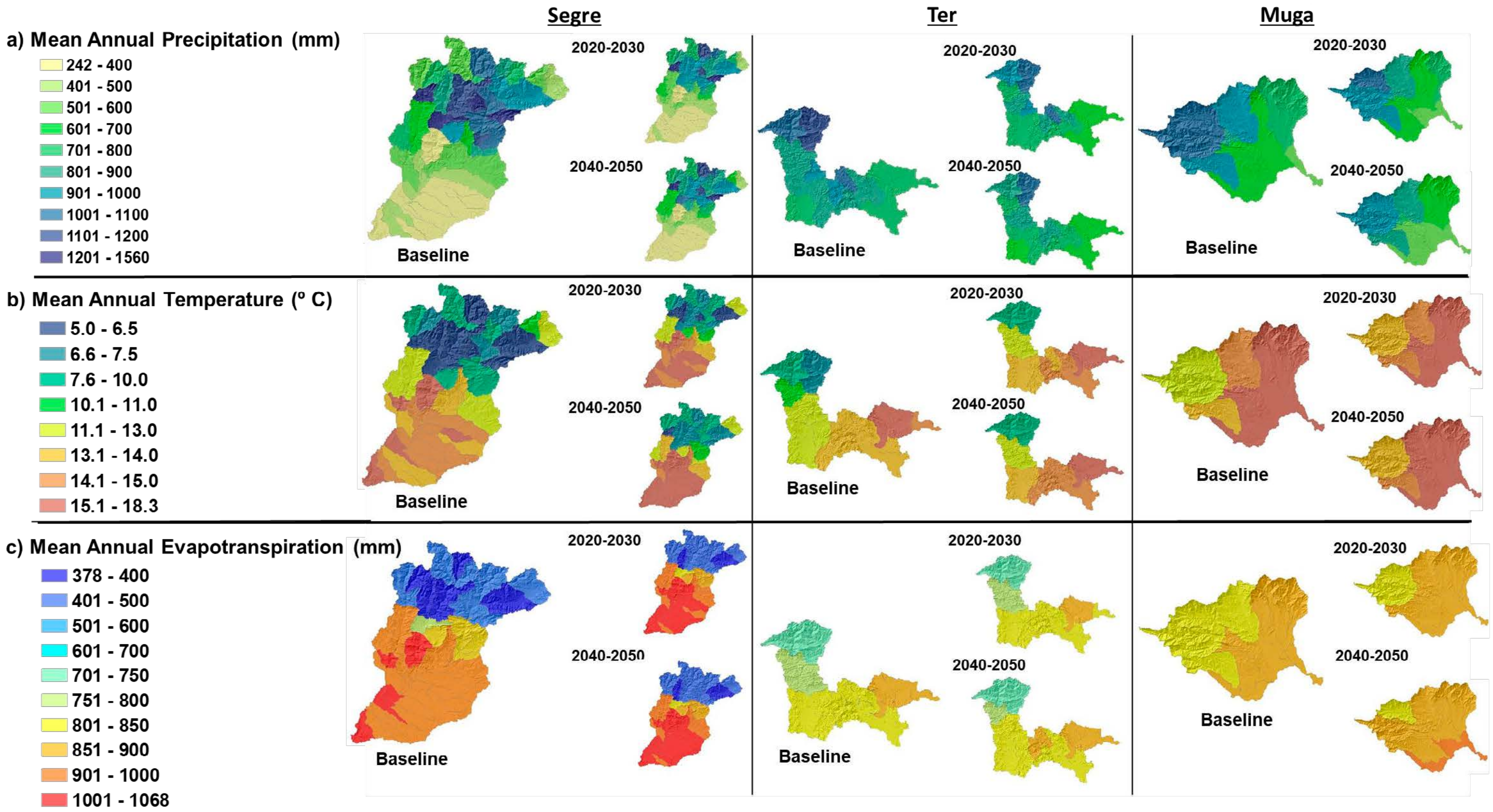

Figure A.4. Overview of the spatial distribution at the subbasin level of: a) mean annual precipitation (mm); b) mean annual temperature and c) mean annual evapotranspiration in the three study-case basins (Segre, Ter and Muga) for the baseline period (2002-2011) and the both future decades analyzed under the RCP 4.5 scenario: 2020s (2021-2030) and 2040s (2041-2050).

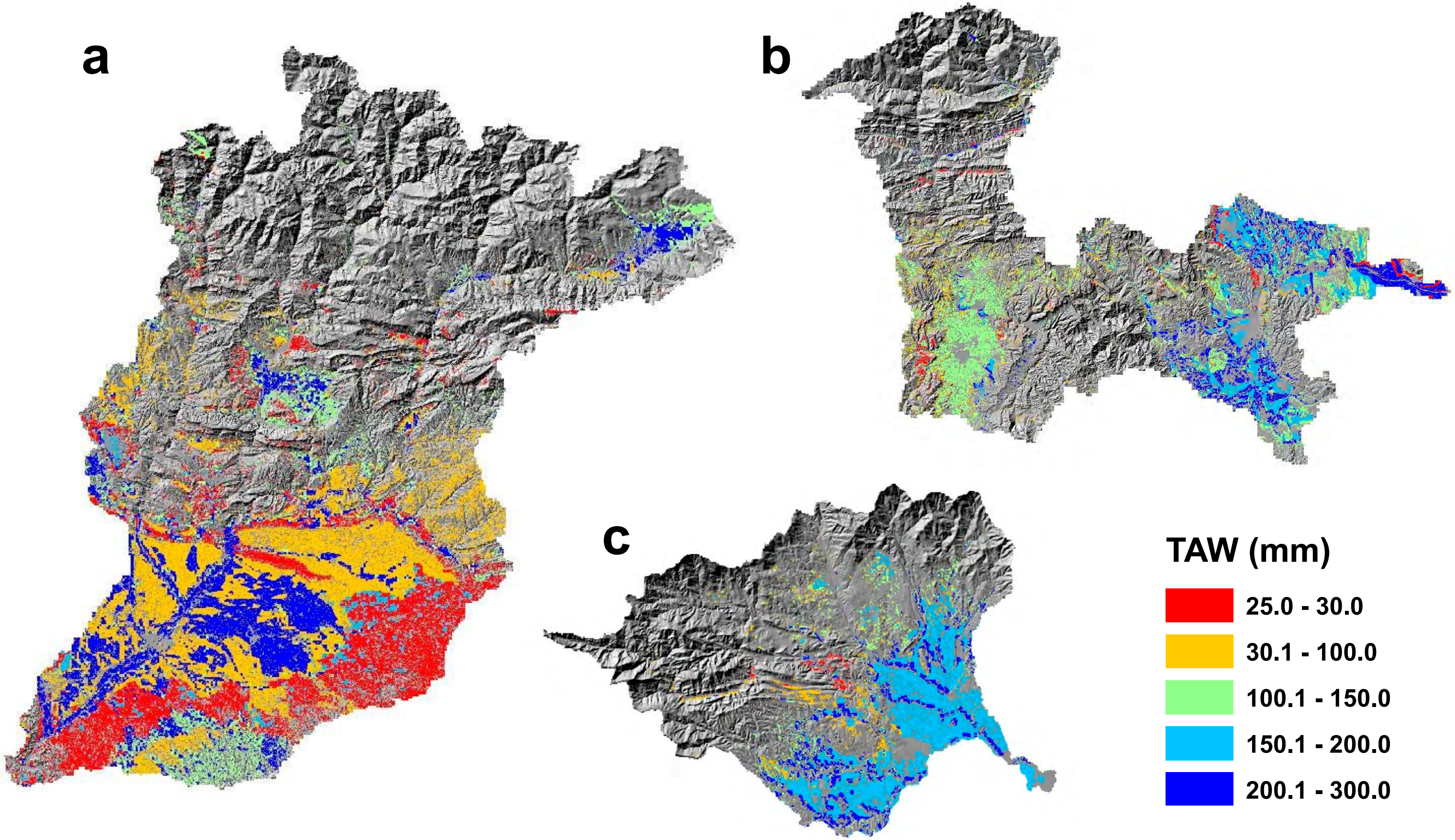

Figure A.5. Spatial distribution of the maximum available water capacity of agricultural soils (TAW in mm) in: a) Segre, b) Ter and c) Muga basins. Greyscale hillshading represents topography of non-agricultural areas.

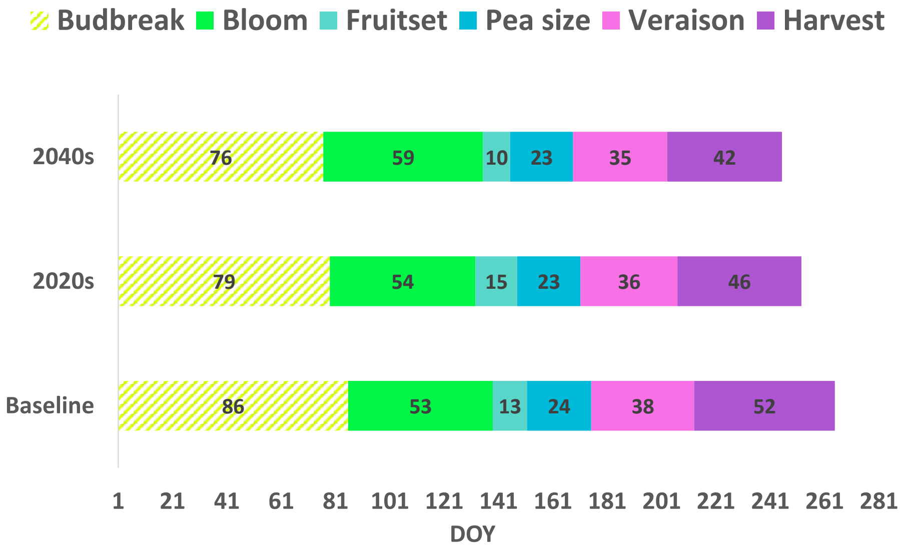

Figure A.6. Time-sequence representation of phenological stages date *(DOY pheno)* of vine growth from 1st October in the lower Segre basin. Numbers inside each colour bar, are number of days in reach each phenological stage *(Days pheno* represented as the end of each colour bar). All data are averaged through the corresponding term: 2020s (2021-2030), 2040s (2041-2050) and Baseline (2002-2011). DOY is day of year.

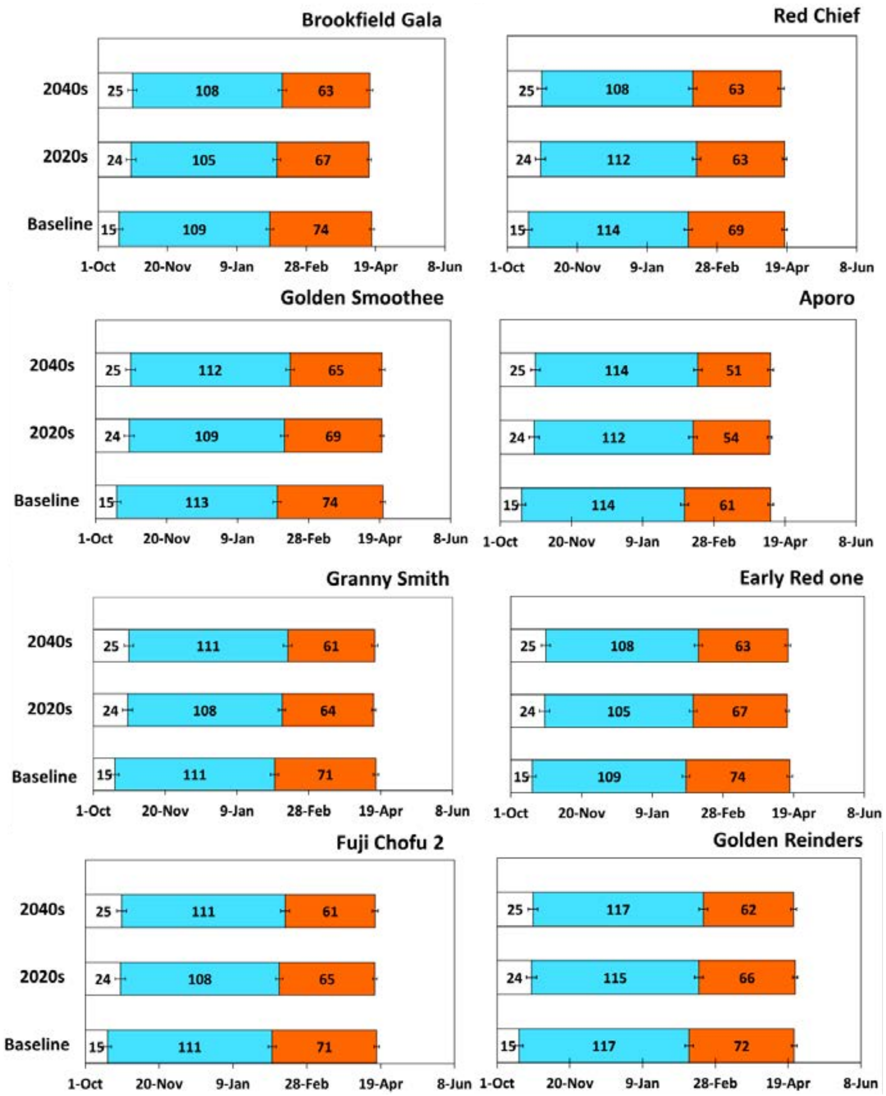

Figure A.7. Time-sequence representation of the chilling (blue colour bar) and heat (red colour bar) phases to F2 flowering stage (anthesis of 50% of the flowers) in a RCP 4.5 climate change scenario for eight apple cultivars in the lower Ter basin segment. Numbers represent duration in days of each phase. Days to beginning of chill phase are counted from 1st October (white colour bar). All data are averaged through the corresponding term: 2020s (2021-2030), 2040s (2041-2050) and baseline (2002-2011). Bars at the end of each strip represent standard error of the mean, representing variability in each period in completing each phase. These bars do not represents the phenology model RMSE or uncertainties related to climate projections.

Table A.1. Mean net irrigation requirements (NIR; m^3/ha) of major crops in the three segments of Segre basin during the baseline (2002-2011) during the 2020s (2021-2030) and the 2040s (2041-2050) and percentage of NIR increments (in brackets).

		m^3/ha	m^3/ha (Δ%*)	
Crop	**Basin Segment**	**Baseline**	**2020s**	**2040s**
Maize	Lower Segre	4,536	4,726 (+4.2%)	4,745 (+4.6%)
	Middle Segre	1,574	1,721 (+9.4%)	1,774 (+12.7%)
	Upper Segre	0	0	0
Alfalfa	Lower Segre	4,320	4,797 (+11.0%)	4,893 (+13.3%)
	Middle Segre	1,901	2,153 (+13.3%)	2,195 (+15.5%)
	Upper Segre	0	0	0
Pastures	Middle Segre	1,476	2,144 (+45.2%)	2,206 (+49.4%)
	Upper Segre	372	327 (-12.0%)	343 (-7.8%)
Barley	Lower Segre	1,065	1,521 (+42.8%)	1,440 (+35.2%)
	Middle Segre	1,065	1,163 (+9.2%)	1,121 (+5.2%)
	Upper Segre	4	13 (+191.3%)	11 (+143.6%)
Wheat	Lower Segre	2,116	2,207(+4.3%)	2,128 (+0.6%)
	Middle Segre	1,562	1,690 (+8.2%)	1,660 (+6.3%)
	Upper Segre	24	7 (-71.58%)	8 (-67.7%)
Olives	Lower Segre	2,937	3,348 (+14.0%)	3,448 (+17.4%)
	Middle Segre	1,631	1,708 (+4.7%)	1,737 (+6.5%)
	Upper Segre	0	0	0
Vines	Lower Segre	702	756 (+7.6%)	811 (+15.4%)
	Middle Segre	364	394 (+8.5%)	411 (+13.1%)
Almond	Lower Segre	4,105	4,352 (+6.0%)	4,455 (+8.5%)
	Middle Segre	1,944	2,177 (+12.0%)	2,235 (+14.9%)
Peach	Lower Segre	3,601	3,658 (+1.6%)	3,709 (+3.0%)
Apple	Lower course	3,283	3,521 (+7.3%)	3,626 (+10.5%)
	Upper course	0	0	0

*percentage of annual NIR increments respect the baseline period.

Table A.2. Mean net irrigation requirements (NIR; m³/ha) of major crops in the three segments of Ter basin during the baseline (2002-2011) during the 2020s (2021-2030) and the 2040s (2041-2050) and percentage of NIR increments (in brackets).

		m³/ha	m³/ha (Δ%*)	
Crop	**Basin Segment**	**Baseline**	**2020s**	**2040s**
Maize	Lower Ter	2,190	2,273 (+3.8%)	2,388 (+9%)
	Middle Ter	2,129	2,294 (+7.7%)	2,425 (+13.9%)
	Upper Ter	0	0	7
Ray-grass	Lower Ter	3,769	3,946 (+4.7%)	4,204 (+11.5%)
	Middle Ter	3,156	3,349 (+6.1%)	3,654 (+15.8%)
	Upper Ter	1,691	1,937 (+14.5%)	2,062 (+21.9%)
Wheat	Lower Ter	886	800 (-9.6%)	840 (-5.1%)
	Middle Ter	1,159	1,161 (+0.1%)	1,271 (+9.6%)
	Upper Ter	899	932 (+3.8%)	989 (+10.1%)
Apple	Lower Ter	2,074	2,135 (+2.9%)	2,250 (+8.5%)
	Middle Ter	1,433	1,581 (+10.3%)	1,780 (+24.2%)
Hazel	Lower Ter	920	923 (+0.4%)	1,047 (+13.9%)
	Middle Ter	490	576 (+17.5%)	666 (+36.0%)

*percentage of annual NIR increments respect the baseline period.

Table A.3. Mean net irrigation requirements (NIR; m³/ha) of major crops in the three segments of Muga basin during the baseline (2002-2011) during the 2020s (2021-2030) and the 2040s (2041-2050) and percentage of NIR increments (in brackets).

		m³/ha	m³/ha (Δ%*)	
Crop	**Basin Segment**	**Baseline**	**2020s**	**2040s**
Maize	Lower Muga	2,336	2,357 (+0.9%)	2,356 (+0.8%)
	Middle Muga	2,197	2,241 (+2.0%)	2,283 (+3.9%)
Alfalfa	Lower Muga	3,917	4,027 (+2.8%)	4,246 (+8.4%)
	Middle Muga	3,067	3,139 (+2.3%)	3,406 (+11.1%)
	Upper Muga	2,473	2,556 (+3.4%)	2,725 (+10.2%)
Pastures	Middle Muga	3,247	3,349 (+3.1%)	3,614 (+11.3%)
	Upper Muga	2,443	2,514 (+2.9%)	2,678 (+9.6%)
Barley	Lower Muga	185	160 (-13.3%)	143 (-22.8%)
	Middle Muga	176	148 (-15.6%)	156 (-11.4%)
	Upper Muga	510	463 (-9.2%)	543 (+6.5%)
Olive	Lower Muga	1,192	1,223 (+2.5%)	1,334 (+11.8%)
	Middle Muga	864	944 (+9.3%)	1,073 (+24.3%)
Vines	Middle Muga	73	78 (+7.8%)	80 (+10.5%)

*percentage of annual NIR increments respect the baseline period.

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Chapter 4

Appendix B.

Methodological details

Details about climate data processing

Candidate series with more than 30 years of data were chosen. For each candidate, the 10 best reference series with at least 3 years overlapped were selected from a correlation matrix between each candidate series and the rest ones (reference series). In the case of precipitation, series were transformed to quantiles series based on their empirical cumulative distribution function, and the gaps in candidate series were filled with the quantile values of a reference series; then the values of the obtained quantiles in the reconstructed series were calculated. In the case of temperature series, the gaps were filled with simple regression between the candidate series and its best correlated reference series, following an iterative approach to guarantee that all the existing data gaps are completed using only the candidate series of each variable. At the end of the quality control we obtained 95 precipitation and 76 temperature series. We did not fill periods prior the creation of each meteorological observatory as recommended by the World Meteorological Organization. Finally, monthly averaged values of daily maximum and minimum temperature and monthly accumulations of daily precipitation were computed and homogenized using HOMER (Mestre et al., 2013). More detailed information about climate data processing can be in Vicente-Serrano et al. (2010) and Vicente-Serrano et al. (2014) and the references therein.

Details about meteorological parameter regionalization at the subbasin scale.

Each subbasin was assigned the meteorological data of the weather station nearest to their centroid. In order to account for orography effects on precipitation and temperature, we used the capability of SWAT to establish up to 10 elevation bands at the subbasin level. Precipitation and temperatures (maximum and minimum) were adjusted for each band as a function of the parameter gradient and the difference between the weather station elevation and the average elevation for each band (Neitsch et al., 2005). Finally, subbasin averaged values were calculated. These averaged values were then used in the remainder modelling.

Details about crop mapping

The crop map at species level was created for each basin within Catalonia boundaries from mainly two sources: (i) Declaration of eligible agricultural area for Common Agricultural Policy payments of Government of Catalonia for the year 2013 (DUN, 2013) and (ii) Farming Land Geographical Information System for the year 2013 (SIGPAC, 2013, acronym in Spanish). DUN 2013 is integrated only by alphanumeric information for each agricultural plot, such as reference code, crop (species level), crop type (arable land, orchards, citric, etc.), water regime, surface and other attributes. SIGPAC 2013 is a geographical information system based on vector data, composed by polygons that spatially represent the agricultural plots. Each feature has associated attributes such as a reference code, crop type, water regime, surface, slope, and other geographical attributes. Both sources were related through the reference code of each agricultural plot by joining the alphanumeric information of DUN 2013 to the features of SIGPAC 2013 thus obtaining a crop map at species level (vector map). Similar regional information from the part of Aragón and Andorra were added to the final crop map SIGPAC 2014 and the farm register information of the Andorra government for the year 2014, respectively). For the French zone, we used two sources of information: the French Graphic Plot Register 2012 (RGP; acronym in French) and Corine land cover 2006 (CLC 2006). More details about the crop map elaboration are explained in Vicente-Serrano et al. (2014).

Details about soil mapping methodology

A Digital Soil Map (DSM) was developed for each basin by expert soil scientists from the European Topic Centre on Urban, Land and Soil Systems (ETC-ULS), based on the spatial correlation between the most relevant soil properties and environmental variables (climate, topography or geology). Soils were classified by a cluster analysis to synthetize the number of soil classes. Moreover, it was feasible to develop singular soil maps with specific properties (such as bulk density, organic matter content, etc.), in addition to taxonomic classification. The data sources used to generate these DSM were:

the Soil Map of Catalonia (very fragmented and specific only for some agricultural areas of Catalonia), the European Soil Map, data from soil profiles from specific studies and the European Soil Database, the Geologic Map of Catalonia, the Digital Elevation Map and the C Content Map in forest soils (Spain). More details about the methodology followed up and the input data needed to create the soil data are extensively explained in Vicente-Serrano et al. (2014).

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