UNIVERSIDAD DE SEVILLA

DEPARTAMENTO DE CRISTALOGRAFÍA,
MINERALOGÍA Y QUÍMICA AGRÍCOLA

MODELIZACIÓN DE LA CAPACIDAD DE SECUESTRO DE CARBONO EN SUELOS MEDITERRÁNEOS

Modelling carbon sequestration capacity in Mediterranean soils

evenor tech™
Spin-Off of CSIC
CSIC

MED_Soil
Research Group

DEPARTAMENTO DE CRISTALOGRAFÍA,
MINERALOGÍA Y QUÍMICA AGRÍCOLA

MODELIZACIÓN DE LA CAPACIDAD DE SECUESTRO DE CARBONO EN SUELOS MEDITERRÁNEOS

Modelling carbon sequestration capacity in Mediterranean soils

Memoria que presenta Dª. Miriam Muñoz Rojas para optar al grado de Doctor

por la Universidad de Sevilla

DEPARTAMENTO DE CRISTALOGRAFÍA,
MINERALOGÍA Y QUÍMICA AGRÍCOLA

MODELIZACIÓN DE LA CAPACIDAD DE SECUESTRO DE CARBONO EN SUELOS MEDITERRÁNEOS

Modelling carbon sequestration capacity in Mediterranean soils

La autora

Miriam Muñoz Rojas

Los directores:

Antonio Jordán López　Lorena M. Zavala　María Anaya Romero

Sevilla, 2012

PREMIOS

Outstanding Student Poster Award. European Geosciences Union General Assembly, 2012. Viena, Austria.

BECAS Y AYUDAS

Contrato I+D+I Torres Quevedo. Subprograma Torres Quevedo. Ministerio de Ciencia e Innovación (MICINN-PTQ), 2010-2013.

Young Scientist's Travel Award for Europeans**.** European Geosciences Union General Assemly, 2012.

Conference Grant for Early Stage Researchers. European Cooperation in Science and Technology (COST), 2011.

PATENTES Y MARCAS

Propiedad Intelectual CarboSOIL: Sistema para evaluar la capacidad de secuestro de carbono de los suelos mediterráneos.
Tipo: Software. Registro: 201299901463385 (11/10/12). Autores: María Anaya Romero, Miriam Muñoz Rojas, Diego de la Rosa, Lorena Martínez Zavala, Antonio Jordán López, Félix González Peñaloza, Rafael Pino Mejías.

PUBLICACIONES

Parte de los resultados obtenidos durante la realización de la presente tesis doctoral han sido publicados en los siguientes trabajos:

ARTÍCULOS EN REVISTAS

M Muñoz-Rojas, A Jordán, L M Zavala, D De la Rosa, M Anaya-Romero. Modelling soil organic C stocks in climate change scenarios: a CarboSOIL application. En revisión.

M Muñoz-Rojas, A Jordán, L M Zavala, D De la Rosa, S.K. Abd-Elmabod, M Anaya-Romero. Impact of land use and land cover changes on organic carbon stocks in Mediterranean soils (1956-2007). Land Degradation & Development. Aceptado.

M Muñoz-Rojas, A Jordán, L M Zavala, D De la Rosa, S.K. Abd-Elmabod, M Anaya-Romero (2012) Organic carbon stocks in Mediterranean soil types under different land uses (Southern Spain). Solid Earth. Aceptado.

M Muñoz-Rojas, A Jordán, L M Zavala, D de la Rosa, S K Abd-Elmabod, M Anaya-Romero (2012). Effect of land use and land cover changes on carbon sequestration in vegetation and soils between 1956 and 2007 (southern Spain). Geophysical Research Abstracts 14: 435-1.

M Muñoz-Rojas, A Jordán, L M Zavala, D de la Rosa, S K Abd-Elmabod, M Anaya-Romero (2012). Spatial analysis for assessing soil organic carbon stocks in southern Spain. Geophysical Research Abstracts 14: 439-2.

M Anaya-Romero, **M Muñoz-Rojas**, R Pino, A Jordán, L M Zavala, D de la Rosa (2012) Carbosoil, a land evaluation model for soil carbon accounting. Geophysical Research Abstracts 14:7227.

M Muñoz-Rojas, D de la Rosa, L M Zavala, A Jordán, M Anaya-Romero (2011). Changes in land cover and vegetation carbon stocks in Andalusia, Southern Spain (1956-2007). Science of the Total Environment 409:2796-2806.

CONGRESOS INTERNACIONALES

M Muñoz-Rojas, A Jordán, L M Zavala, D de la Rosa, S K Abd-Elmabod, M Anaya-Romero (2012). Effect of land use and land cover changes on carbon sequestration in vegetation and soils between 1956 and 2007 (southern Spain). European Geosciences Union, General Assembly 2012. Viena, Austria.

M Muñoz-Rojas, A Jordán, L M Zavala, D de la Rosa, S K Abd-Elmabod, M Anaya-Romero (2012). Spatial analysis for assessing soil organic carbon stocks in southern Spain. European Geosciences Union, General Assembly 2012. Viena, Austria.

M Anaya-Romero, **M Muñoz-Rojas**, R Pino, A Jordán, L M Zavala, D de la Rosa (2012) Carbosoil, a land evaluation model for soil carbon accounting. European Geosciences Union, General Assembly 2012. Viena, Austria.

M Anaya-Romero, **M Muñoz-Rojas**, R Pino, A Jordán, L M Zavala, D de la Rosa (2012). Carbosoil, a land evaluation model for maximizing carbon sequestration in Mediterranean soils. EUROSOIL2012, European Confederation of European Soil Science Societies. Bari, Italia.

M Muñoz-Rojas, A Jordán, L M Zavala, M Anaya-Romero (2012). Impacts of Land use/Land Cover Changes on Vegetation and Soil Carbon Stocks in Southern Spain (1956-2007). Planet under Pressure 2012, International Geosphere-Biosphere Programme, Diversitas, International Human Dimensions Programme on Global Environmental Change, World Climate Research Programme, Earth System Science Partnertship. Londres, Reino Unido.

M Muñoz-Rojas, A Jordán, L M Zavala, D De la Rosa, M Anaya-Romero (2011). Spatial analysis to determine Mediterranean soil organic carbon stocks. En: Conferencia Europea ESRI 2011, 26-28 October 2011. Enviromental Systems Research Institute. Madrid, España.

CONGRESOS NACIONALES

M Muñoz-Rojas, M Anaya-Romero, L M Zavala, A Jordán, D de la Rosa (2011). Effects of land use / land cover changes in vegetation carbon stocks in Southern Spain between 1956 and 2007. En: V Simposio Nacional sobre Control de la Degradación y Uso Sostenible del Suelo. SECS. Murcia, España

M Muñoz-Rojas, M Anaya-Romero, L M Zavala, A Jordán, D de la Rosa (2011). Impact of land use changes and management in soil organic carbon stocks in Andalusia (Southern Spain). En: V Simposio Nacional sobre Control de la Degradación y Uso Sostenible del Suelo. SECS. Murcia, España

Esta tesis doctoral ha sido parcialmente financiada por el Subprograma Torres Quevedo del antiguo Ministerio de Ciencia e Innovación, con número de expediente PTQ-10-02582, y por la Consejería de Economía, Innovación y Ciencia de la Junta de Andalucía a través del proyecto 851238 “Desarrollo del e-sistema CARBOSOIL para evaluar la capacidad de secuestro de carbono de los suelos en Andalucía. Integración de factores de mitigación al cambio climático en el sistema MicroLEIS”.

AGRADECIMIENTOS

En estos últimos años he tenido la suerte de poder retomar la ciencia y de tener cerca a personas que de una forma u otra me han aportado grandes cosas y han hecho posible que esto saliera adelante. Ahora llega el momento de dar las gracias a todos.

Tengo muchísima de suerte de haberme encontrado a Antonio y Lorena. Me acuerdo como si fuera ayer del primer día que llegue a vuestro despacho con la “loca idea” de hacer una tesis doctoral. Desde ese momento, no solo me habéis enseñado infinidad de cosas y me habéis hecho pasar muy buenos momentos sino que me habéis motivado y apoyado, haciéndome sentir que puedo hacer lo que me proponga (como os digo siempre, creo que me tenéis algo sobrevalorada…). Sois los mejores directores de tesis que uno podría desear y espero que sigamos siendo siempre amigos, haciendo ciencia, riéndonos de nuestras tonterías y tomando Tom Collins.

Detrás de cada tesis hay una idea y un proyecto, y quiero darte las gracias, María, por haberme dado la oportunidad de trabajar en CarboSOIL y por tu gran esfuerzo en que todo salga adelante. Has sido una estupenda directora de tesis y coordinadora del proyecto. Me siento afortunada por tener cerca a un experto como Diego de la Rosa, al que le quiero agradecer sus valiosos comentarios y consejos.

Ha sido también fundamental la participación de Rafael del Pino en esta tesis doctoral, al que le doy las gracias por su ayuda en el manejo de técnicas estadísticas y en la elaboración del modelo.

I would like to acknowledge Rafat Ali and Fernando Martins for the review of the thesis and Paulo Pereira for his useful comments. I would also like to thank Joep Crompvoets for his guidance and support during my Master studies in Wageningen. A Cecilio Oyonarte le doy también las gracias por haberme dado una primera oportunidad en la ciencia y por introducirme en el mundo de los suelos. Gracias también a Artemi Cerdá por la difusión de la investigación realizada en esta tesis.

Si hay alguien que ha estado a mi lado todo este tiempo (literalmente en el ordenador de al lado) y que ha sido un gran compañero y apoyo, ese es Sameh, con el que he aprendido no solo de suelos sino muchas cosas más, incluido el árabe (aunque seguimos en el vocabulario básico...). Gracias amigo.

Quiero agradecer a mis compañeros del grupo MED_Soil su colaboración y su apoyo: Arturo, Gema, Nicolás, Juan Gil, Jorge Mataix, Colin, Helena, etc. En especial le doy las gracias a Félix, mi compañero experto en GIS, por su ayuda con la informatización del modelo. Angeluki y Jorge, gracias por las risas y los buenos ratos que pasamos en Murcia. Los congresos no son lo mismo sin vosotros, como dice Paloma, con la que tuve la suerte

de contar también como compañera en Viena. Gracias también a Ale por sus palabras de ánimo.

En estos dos años y medio han pasado unos cuantos compañeros por la oficina (Lucas, Yameli, etc) a los que quiero agradecer su apoyo. En especial a Gianni que se ha ofrecido siempre sonriente a ayudarme, a Alessio, por su asesoramiento en los temas de “diseño” y a Zoha, mi buena amiga y compañera que siempre me ha dado excelentes consejos. Durante todo este tiempo he compartido desayunos y charlas con los compañeros del grupo de Riego y Ecofisiología de Cultivos del IRNAS, a los que agradezco esos buenos ratos juntos, en especial a Virginia que se ha convertido en una buena amiga. Gracias también a Antonio Rosales y resto de compañeros del IRNAS.

Mis amigas Paula, Pitu, Moni y Bárbara, que ya me advirtieron de que esto no era tarea fácil, han sido siempre un referente para mí. Desde Holanda hasta Sevilla pasando por Almería habéis sido siempre un gran apoyo y unas excelentes amigas a las que adoro. Gracias también a todos los “Wagenianos”. A mis niñas de Aguadulce (Ana, Ara, Marta, Miri, Sandra, Temis) les doy las gracias por su ánimo y su cariño. Me siento afortunada de teneros como amigas todos estos años. También quiero dar las gracias a mis amigos en Almería (muchos), Madrid (María, Patri), Málaga, Segovia, Francia (Adri y Bini), Holanda, Croacia, etc., por estar ahí cuando os he necesitado. Por supuesto la vida en Sevilla no sería igual sin mis amigos sevillanos (y los no sevillanos residentes en Sevilla). En especial le doy las gracias a Ana y Edu, que además de enseñarme los mejores bares de tapas de la ciudad y hacerme pasar momentos muy divertidos, han estado conmigo en los malos ratos también. Os echamos mucho de menos.

De forma muy especial les doy las gracias a mis padres y mi hermana Irene por su cariño y su apoyo incondicional en todos los momentos de mi vida. Aunque no estemos tan cerca ahora, habéis estado siempre a mi lado ayudándome en todo lo que me he propuesto, y haciendo posible mis logros, incluida esta tesis. Gracias también al resto de mi familia, incluido Javi.

Željela bih se zahvaliti Darku, Slavenki i Lari, mojoj hrvatskoj obitelji, za svu njihovu ljubav i podršku.

Y mis últimas palabras son para mi marido, Ozren. Es un lujo tener en casa a un gran científico que me aconseja y me ayuda en mi trabajo, Dr. Oz, pero sobre todo, eres una persona increíble que has estado a mi lado todo este tiempo, queriéndome, cuidándome y haciéndome reír (incluso cuando estoy muy enfugada). No hubiera podido conseguir esto sin ti. In the words of Led Zeppelin: *Today, my world it smiles, your hand in mine, we walk the miles; thanks to you it will be done, for you to me are the only one*.

Todo fluye, nada permanece. Lo único constante es el cambio.

Heráclito de Éfeso

A mis padres

CONTENTS

SUMMARY

MODELLING SOIL CARBON SEQUESTRATION CAPACITY IN MEDITERRANEAN SOILS

During the last decades, land use changes have largely affected the global warming process through emissions of CO_2. However, C sequestration in terrestrial ecosystems could contribute to the decrease of atmospheric CO_2 rates in the short- or medium-term. Under the Kyoto Protocol (UNFCCC, 1997), national governments are required to assess and report national atmospheric C emissions and removals reflected as changes in C pools. Accordingly, regional studies for assessing C stocks are needed. It is essential to predict soil organic C (SOC) stocks in future climate scenarios to establish adequate land use and management strategies. Models are effective tools for assessing SOC stocks and dynamics at different scales and predict C sequestration trends under projected scenarios. Soil C models are increasingly being used as decision support tools, in particular on issues related to land use or climate change. Although Mediterranean areas show a high potential for C sequestration, only a few studies have been carried out in Mediterranean systems. Several studies on soil C models in combination with climate change scenarios have been developed but new tools are needed to improve soil organic C stocks predictions.

After the general introduction (Chapter 1) Chapter 2 improves and tests methodologies to assess land cover change (LCC) dynamics between 1956 and 2007 in Andalusia (Southern Spain) and temporal and spatial variability of C stored in vegetation at a wide scale. LCCs are assessed by comparison of spatial data from 1956 and 2007 and are reclassified following land cover flows reported in major areas in Europe. Southern Spain has supported important changes during the studied period with significant consequences for vegetation C stocks, mainly due to afforestation and intensification of agriculture, resulting in a total vegetation C stock of 156.08 Tg in 2007, with an increase of 17.24 Tg since 1956. Likewise, LCCs in the 51-year period (1956-2007) have largely affected C stored in soils in Southern Spain. In Chapter 3 a methodology is proposed to assess the impact of land use and land cover change (LULCC) dynamics on SOC contents at different depths. Soil databases and spatial datasets with soil and land use information are used to estimate SOC stocks. Additionally, SOC sequestration rates are provided for different LCCs and soil types in Andalusia. A total of 16.8 Tg of SOC has been lost in the last years (approximately 0.33 Tg year^{-1}) and largest decreases were observed in soils types as Fluvisols and Arenosols and land use types as coastal wetlands. On the other hand, forests

contributed to sequestration of 8.62 Mg C ha^{-1} (with a sequestration rate of 25.4%). Chapter 4 focuses on assessing current SOC contents and identifying environmental factors which determine fluctuations and intensity of SOC dynamics. Soil and climate databases, digital elevation models and land use and soil maps were used to evaluate SOC pools and their distribution within the soil profile. The total organic C stock in 2007 in soils of Andalusia is 415 Tg for the upper 75 cm, with up to 55% stored in the top 25 cm of soil (229.7 Tg). Among all soil types, Calcisols and Vertisols show the highest values with above 65 Mg C ha^{-1} (0-75 cm). Significant correlations have been found between soil organic C and some environmental factors in natural areas, such as average summer and winter temperatures, annual mean precipitation and elevation.

These previous studies in Chapters 2, 3 and 4, comprise the first comprehensive analysis of the impacts of land use changes on terrestrial C stocks at a regional scale in Andalusia (S Spain). Based on this preliminary research, a soil carbon model (CarboSOIL) has been developed to predict SOC stocks at different soil depths for a range of soil management, land use and climate change scenarios (Chapter 5). Several methodologies have been tested to design the new tool CarboSOIL and better predictions have been obtained with Multiple Linear Regression techniques and Box-Cox transformation procedures. The model has been trained in Andalusia and tested in Valencia, and is divided in four submodels (CarboSOIL25, CarboSOIL50, CarboSOIL75 and CarboSOIL TOTAL) according to different soil depths (0-25 cm, 25-50 cm, 50-75 cm and 0-75 cm). CarboSOIL model has been developed as a computer application to be implemented in the agroecological decision support system MicroLEIS, and each submodel has been built as a spatial tool in a GIS environment for spatial analysis of the inputs/outputs of the model. In Chapter 6, CarboSOIL has been tested and validated in Andalusia in the baseline scenario and applied in different IPCC scenarios (A1B, A2 and B1) according to different Global Climate Models (BCCR-BCM2, CNRMCM3 and ECHAM5). Output data was linked to spatial datasets (soil and land use) and spatial analysis were performed to quantify SOC stocks in different soil types under a range of land uses. Although there is an overall trend in all soil types towards decreasing of SOC stocks in the upper soil sections (0-25 cm and 25-50 cm), predicted SOC stocks tend to increase in the deeper soil section (50-75 cm). CarboSOIL model proved its ability to predict the short, medium and long-term trends (2040, 2070 and 2100) of SOC dynamics and sequestration under projected future scenarios of climate change.

RESUMEN

MODELIZACIÓN DE LA CAPACIDAD DE SECUESTRO DE CARBONO EN SUELOS MEDITERRÁNEOS

Durante las últimas décadas, los cambios de uso del suelo han afectado en gran medida al proceso de calentamiento global a través de emisiones de CO_2. No obstante, la captura o secuestro de carbono (C) en los ecosistemas terrestres podría contribuir a la disminución de las tasas de CO_2 atmosférico a corto o medio plazo. En el marco del Protocolo de Kioto de las Naciones Unidas (1997), los gobiernos nacionales tienen la obligación de evaluar e informar sobre las emisiones y absorciones de CO_2, lo que se refleja en los cambios producidos en los distintos reservorios de carbono. De esta forma, son necesarios estudios regionales para la evaluación los contenidos de carbono, siendo esencial la predicción del mismo en escenarios futuros de cambio climático para poder establecer un uso y manejo adecuado del suelo. Los modelos son herramientas de gran utilidad para la evaluación de los contenidos de carbono orgánico del suelo y su dinámica a diferentes escalas, así como para predecir las tendencias en el secuestro de carbono bajo distintos escenarios. Los modelos de predicción de C en los suelos son cada vez más utilizados como herramientas de ayuda a la decisión, en particular, en cuestiones relacionadas con el uso del suelo o el cambio climático. A pesar de que el área mediterránea muestra un alto potencial para el secuestro de C, son pocos los estudios que se han llevado a cabo en esta zona. En estudios previos, se han desarrollado diversos trabajos de modelización del C del suelo en combinación con escenarios de cambio climático, pero todavía son necesarias nuevas herramientas para mejorar las predicciones de las reservas de C orgánico del suelo.

Tras la introducción general (capítulo 1), el capítulo 2 mejora y propone nuevos métodos para la evaluación de la dinámica de los cambios de de uso del suelo entre los años 1956 y 2007 en Andalucía (sur de España) y la variabilidad temporal y espacial a gran escala del carbono almacenado en la vegetación. Se han evaluado los cambios de uso del suelo mediante la comparación de datos espaciales de 1956 y 2007, y se han reclasificado siguiendo flujos de cambio de uso previamente establecidos en Europa. La región andaluza ha sufrido cambios significativos durante el período estudiado, lo que ha traído importantes consecuencias para las reservas de C en la vegetación, principalmente debido a la reforestación y la intensificación de la agricultura. Con un incremento del 17.24 Tg desde 1956, los contenidos totales de C en este reservorio son de 156.08 Tg en la actualidad (2007). A su vez, los cambios de uso producidos en estos 51 años (1956-2007) han afectado de forma intensa al carbono almacenado en los suelos del sur de España.

En el capítulo 3 se propone una metodología para evaluar el impacto de los cambios de uso en los contenidos de carbono orgánico del suelo (COS) a diferentes profundidades a lo largo del perfil. Para ello, se han utilizado bases de datos de suelos georeferenciadas y un conjunto de datos espaciales de suelos y vegetación para determinar las existencias de COS. Además, se han estimado tasas anuales de secuestro de C para los distintos usos y tipos de suelo en Andalucía. En los últimos años se ha perdido un total de 16.8 Tg de C orgánico en el suelo (aproximadamente 0.33 Tg anuales) y los mayores descensos se observaron en Fluvisoles y Arenosoles y en los humedales costeros. Por otro lado, en el mismo periodo los bosques han contribuido a la acumulación de 8,62 Mg ha^{-1} C orgánico en el suelo, lo que equivale a una tase de secuestro de C del 25,4%. El capítulo 4 se centra en la evaluación de los contenidos actuales de carbono orgánico del suelo (COS), identificando los principales factores ambientales que intervienen en las fluctuaciones y en la intensidad de la dinámica del COS. Para ello se han usado bases de datos de suelos y clima, modelos digitales de elevación del terreno y mapas de suelos y de usos del territorio, lo que nos ha permitido evaluar los contenidos de carbono orgánico en el y su distribución a través del perfil del suelo. En el año 2007, los suelos de Andalucía almacenan 415 Tg C orgánico en los primeros 75 cm del perfil, de los cuales un 55% se acumula en los primeros 25 cm del suelo (229.7 Tg). Entre todos los tipos de suelo analizados, Calcisoles y Vertisoles muestran los valores más altos con más de 65 Mg C ha^{-1}(0-75 cm). Se han obtenido correlaciones significativas entre el COS y distintos factores ambientales en las áreas naturales, tales como las temperaturas medias de verano e inviernol, la precipitación media anual y la elevación.

Los estudios realizados en los capítulos 2, 3 y 4, constituyen un exhaustivo análisis de los impactos de los cambios del uso del territorio sobre las existencias de carbono terrestre a escala regional en Andalucía (sur de España). Estas investigaciones preliminares han sido la base para el desarrollo de un modelo de evaluación del C en el suelo (CarboSOIL) que ha sido construido para predecir los contenidos de COS a distintas profundidades y en múltiples escenarios de uso del territorio, manejo del suelo y cambio climático (Capítulo 5). Se han analizado distintas metodologías para el diseño de esta nueva herramienta CarboSOIL, y las técnicas estadísticas que han ofrecido mayor precisión fueron Regresión Lineal Múltiple y la transformación de Box-Cox. El modelo ha sido entrenado en Andalucía y validado en Valencia, y se divide en cuatro submodelos (CarboSOIL25, CarboSOIL50, CarboSOIL75 y TOTAL CarboSOIL) de acuerdo a distintas profundidades del suelo (0-25 cm, 25-50 cm, 50-75 cm y 0-75). CarboSOIL ha sido desarrollado como una aplicación informática que se integra en el sistema agroecológico de ayuda a la decisión MicroLEIS DSS, y cada submodelo ha sido construido como una herramienta espacial en un entorno SIG para el análisis espacial de las distintas entradas y

salidas del modelo. Finalmente, en el capítulo 6, CarboSOIL ha sido ensayado y validado en Andalucía en el escenario actual (escenario base) y ha sido aplicado en diferentes escenarios del Panel Intergubernamental de Cambio Climático (A1B, A2 y B1) de acuerdo a diferentes modelos globales de clima (BCCR-BCM2, CNRMCM3 y ECHAM5). Los datos de salida se han vinculado a conjuntos de datos espaciales (de suelo y uso de la tierra) y se han llevado a cabo diversos análisis espaciales para predecir los contenidos de COS en función de distintos tipos de suelo y en una amplia gama de usos de la tierra. Aunque existe una tendencia general en todos los tipos de suelo a la disminución de las existencias del C orgánico en las secciones superiores del suelo (0-25 cm y 25-50 cm), los resultados obtenidos pronostican un aumento de éstos en las secciones más profundas del suelo (50-75 cm). CarboSOIL ha demostrado su capacidad para predecir las tendencias a corto, medio y largo plazo (2040, 2070 y 2100) de la dinámica del COS y el secuestro de éste, en escenarios futuros de cambio climático.

CHAPTER 1

INTRODUCTION

1.1 Background

Human strains over natural systems have been severely intense over the last 50 years, and the different ecosystems have changed in a larger extent than in any other equivalent period of time. At a global scale, these changes are mainly due to growing demands for food, water, timber, fiber and fuel (Fitter et al., 2010), but different processes must be considered at more detailed scales. Human induced land use/land cover changes (LULLCs) have contributed to ecosystems degradation, more intensely during the last decades in Mediterranean areas (Cerdà et al., 2010). These LULCCs, especially deforestation and agricultural intensification, have extensively affected the global warming process through CO_2 emissions to the atmosphere (Lambin et al., 2001).

With the threat of a dangerous climate change, actions are needed to reduce our emissions of CO_2 and other greenhouse gases (GHG) and to prepare for the impacts of climate change. New energy sources are not yet fully developed and terrestrial C sequestration could make considerable contributions to climate change in the short or medium term. New methods and studies to assess terrestrial C dynamics are necessary to support decision-making in land management and climate adaption strategies (IPCC, 2007).

1.2 Global change and C dynamics

1.2.1 Global change and the global C cycle

Terrestrial ecosystems stores C in the form of plants, animals, soils and microorganisms (bacteria and fungi). Most of this C exists in organic form, which refers to compounds produced by living organisms, including leaves, wood, roots, dead plant material and the brown organic matter in soils (Kutsch et al., 2009). Among terrestrial systems, soils are the largest C sinks, holding approximately 1,500 Pg C in the top meter, with values ranging from 1,400 to 1,600 Pg C. Of this total, approximately 55 Pg C resides in fresh litter, or detritus, on the surface of the soil forest floor. Soil C stocks represent approximately twice the amount of C stored in the atmosphere and in vegetation (Table 1.1). A large proportion of the soil C pool lies near the soil surface, where it is subject to microbial decay, erosion, and disruption by human activities. In the upper 30 cm, soil C stocks in the world account for 684-724 Pg (Batjes, 1996).

Carbon is exchanged between terrestrial aboveground and belowground C stocks and the atmosphere through chemical, physical, geological and biological processes. These processes are part of the C cycle (Figure 1.1). The balance between the total amount of C released to the atmosphere in the form of $CO_{2,}$ and the total amount withdrawn from the atmosphere, determines whether the pool or reservoir is acting as a source (adding C to the atmosphere) or a sink (removing C from the atmosphere). If C sources are equal to C sinks, the C cycle is in equilibrium (Lal, 2004).

Table 1.1 C pools in the World, Europe, Spain and Andalusia. (Source: Batjes, 1999; Brown S., 1998; Goodale et al. 2002 ; Muñoz-Rojas et al., 2011; Muñoz-Rojas et al, 2012; Nabuurs et al., 1997)

Carbon pool	**Global**	**Europe**	**Spain**	**Andalusia**
Oceans	39,000 10^3 Tg	-	-	-
Atmosphere	750 10^3 Tg	-	-	-
Soils	1,500 10^3 Tg*	75 10^3 Tg*	3.8 10^3 Tg*	0.42 10^3 Tg**
Vegetation	650 10^3 Tg	20,6 10^3 Tg	0.6 10^3 Tg	0.16 10^3 Tg

(*) 1 m depth ; (**)75 cm depth

Global warming and climate change are major environmental problems and are considered a consequence of anthropogenic emissions of carbon dioxide (CO_2). Although uncertainties remain regarding the causes, consequences and extent of climate change, the impact of human activities on the energy balance of the earth is a prime concern in the twenty-first century. Human disturbances like the use of fossil carbon and the disruption of terrestrial ecosystems have altered the natural balance of the C cycle (Freibauer et al., 2004). In the last years, the concentration of CO_2 in the atmosphere has Increased to approximately 30%-40% above natural background levels and will continue to

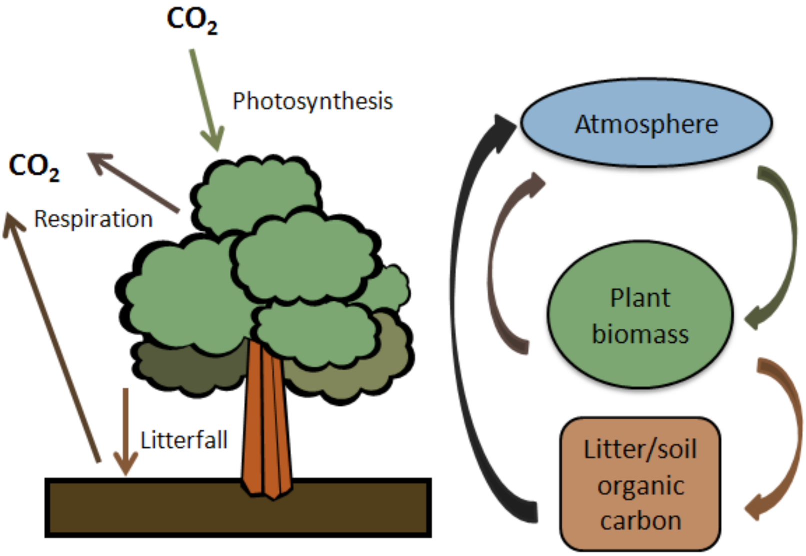


Figure 1.1. Simplified version of the global carbon cycle with main processes in vegetation and soils.

rise in the future. As a consequence, the CO_2 accumulation in the atmosphere has affected the fluxes between the different C pools such as photosynthesis, plant respiration, litterfall and soil respiration (Kutsch et al., 2009).Globally, LULCCs contribute with 25% of the anthropogenic flux of CO_2 to the atmosphere, in a second position after fossil fuels (Houghton et al., 2001) and it has been estimated that $1.6 \pm 0.8\ 10^6$ Mg C $year^{-1}$ are released to the atmosphere. As a result of the human disturbance of soils, especially in agriculture, 36 Pg C has been lost from soils between 1860 and 1960, with a current rate of loss of approximately 0.8 Pg C $year^{-1}$. Thus, the loss of carbon from soils is a significant component of the biotic flux of CO_2 to the atmosphere (IPCC, 2007).

1.2.2 Carbon sequestration of terrestrial ecosystems

Carbon sequestration in terrestrial ecosystems is defined as the net removal of CO_2 from the atmosphere and also the avoidance of CO_2 emissions from these ecosystems into the atmosphere. In vegetation, this removed C is stored as plant biomass (in trunks, branches, leaves and roots) and in soils is stored as organic matter (IPCC, 2000). Carbon sequestration is considered a crucial strategy for reducing atmospheric CO_2 concentration, contributing to alleviate the problem of global warming and climate change mitigation (Lal, 2003). Worldwide, the potential capacity for soil organic carbon (SOC) sequestration has been estimated between 0.4 and 1.2 Gt $year^{-1}$. The balance between inputs of organic matter and C loss by natural conversion to CO_2 and CH_4, erosion or hydrological C export, determines whether the soil is sequestering C (Lal, 2004; Ostle et al., 2009). A number of studies reported that it might be possible to sequester 40 to 80 Pg of C in cropland soils with appropriate management practices over the next 50-100 years. This amount comprises enough C to offset any further increase in the atmospheric inventory for a period between 12 and 24 years. In addition, there is additional C sequestration potential in managed forests and grassland soils (IPCC, 2000; Mol Dijkstra, 2009).

Soil organic C contributes to a variety of important biological, physical and chemical functions, with strong connections between each of them. The use and value of soils are frequently associated with agriculture but they are also relevant for the provision of many other ecosystem services. Soil C contents and dynamics are key determinants of the quantity and quality of these services which includes enhancing cation exchange capacity, improving soil aggregation and water retention and supporting soil biological activity. Furthermore, SOC promotes resistance to soil erosion and helps to regulate flooding by increasing infiltration, reducing runoff and slowing water movement from upland to lowland areas. It also diminishes the release of agrochemicals, pathogens and contaminants to the environment. However, among all ecosystem services, it is remarkable the role that SOC plays in climate regulation (Fitter et al, 2010; IPCC, 2007).

Land use and land cover changes (LULCCs) have important effects on C stocks in soils and vegetation (Eaton et al., 2008; Ostle et al., 2009; Schulp et al, 2008; Smith, 2008). Afforestation of former agricultural land increases the C pool in the aboveground biomass and replenishes the dead organic matter (litter and woody debris) and the soil C pool. Accumulation takes place until the trees mature and the soil reaches a new equilibrium between C inputs (litterfall and rhizodeposition) and C outputs (respiration and leaching). An adequate forest management can increase forest productivity and, thereby, enlarge soil C inputs and avoid high rates of decomposition (Jandl et al., 2007).

Organic C contents in soils tends to decrease when transforming grasslands, forest or other native ecosystems to croplands, and to increase when restoring native vegetation on former croplands, or by restoring organic soils to their native condition (Guo and Gifford, 2002). Nevertheless, although soils converted from natural vegetation to arable land decline in SOC content, after a period of time a new equilibrium level is reached (Dawson and Smith, 2007).There are a wide range of management practices that can enhance SOC levels by either increasing inputs or decreasing losses (Table 1.2). Sustainable agricultural practices that mitigate carbon can have important additional benefits, including increased soil fertility and productivity, improved resistance to drought and extreme weather, and better capacity to adapt to climate change (Wang et al., 2011).

In summary, C sequestration can play a major role to stabilize C emissions to the atmosphere but additionally there are considerable production and environmental co-benefits. These benefits could be achieved in the short term so it can be stated that above and below ground C sequestration is a ‘win-win’ situation.

1.3 Measurement and prediction of soil organic carbon stocks

In general, methods to assess above-ground biomass are more developed than for soil carbon. The three major methods for vegetation carbon assessment include the following (Gibbs et al. 2007): (a) Biome averages, which involves the estimation of average vegetation C stocks for broad vegetation categories based on a range of input data sources, (b) Forest inventory that relates tree diameters or volume to forest C stocks using allometric relationships, and (c) The use of optical, radar, or laser remote-sensing data integrated with allometry and ground measurements. In the past decades, the lack of detailed land cover change databases and appropriate models have been a drawback in C assessment (Lal et al., 2001; Watson et al., 2000, Zhao et al., 2010). However, after the development of remote sensing technologies and geographical information systems, reliable land cover information has been achieved and became available (Herold, 2006). In contrast to vegetation, soil carbon sinks and sources have not received much consideration in current GHG reduction policies, in part due to the lack of understanding by many policy makers and others about the capabilities of measuring soil carbon (Bahn et al., 2009).

Table 1.2. Management practices for soil carbon accumulation in forest and agricultural systems (Source: Jandl et al., 2007; Smith et al, 2004)

Measure	Effect
Forests	
Afforestation	Increases the C pool in the aboveground biomass and replenishes the soil C pool.
Protection of existing forests	Preserves existing SOC stocks and prevents emissions due to biomass burning and land clearing.
Reforestation	Increasing tree cover density in degraded forests increases C accumulation.
Tree species selection	At identical biomass volumes, trees with high wood density (deciduous tree species) accumulate more C than trees with light wood (coniferous species)
Stand management	Harvest residues on the soil surface increase C stocks of the forest floor but disturb soil structure and lead to soil C loss.
Site improvement	N fertilization stimulates biomass production, but leads to GHG emissions.
Grasslands and croplands	
Zero or reduced tillage	Decreases the accelerated decomposition of organic C (and depletion of SOC) associated to intensive tillage. Prevents the breakage of soil aggregates that protect C.
Mulching/residue management/composting	Enhances soil moisture and prevents soil erosion. Crop residues prevent soil C loss. In flooded soils mulching can increase CH4 emissions.
Introduction of earthworms	Improve aeration and organic matter decomposition.
Application of inorganic fertilizers and manure	Adding manures and fertilizers stimulate biomass production. Increases plant productivity and thus SOC However, chemical fertilizers are non-environmentally friendly and result in N2O emissions.
Water management	It can improve plant productivity and production of SOC. However, energy used for irrigation is associated to GHG emissions, and nutrient leaching can affect water quality. Carbon costs of producing fertiliser and pumping irrigation water should be considered.
Improved rotations	Rotations with perennial pastures can increase biomass returned to the soil and therefore enhance SOC. Integration of several crops at the same time can increase organic material, soil biodiversity and soil health, as well as increasing food production.
Site specific management	It may reduce the risk of crop failure and thus improve overall productivity, improving SOC stocks.
Use of improved crop varieties	Increase productivity above and below ground and crop residues, thereby enhancing SOC.

1.3.1 Soil organic carbon stocks distribution

Globally, spatial distribution of SOC reflects rainfall distribution, with larger accumulations of C in more humid areas (Kapos et al., 2008). Therefore, most of the SOC is stored in the northern hemisphere (Figure 1.2). At global scales, SOC pools are difficult to determine because of the high spatial variability and different factors affecting soil C dynamics. Land use is one of the factors with larger influence on SOC stocks (Liebenns et al., 2003; Meersmans et al., 2008; Smith, 2008), altering the balance between carbon losses and carbon sequestration (Ostle et al., 2009). However, there are further determinants influencing SOC variability, such as climate and topography (Schulp et al., 2008; Phackhomphon et al., 2010). Whereas the SOC pool has been studied at global, continental (Eswaran et al., 1993, Liski et al., 2002; Smith, 2004) or regional scales in humid forest systems (Batjes and Dijkshoorn, 1999; Schwartz and Namri, 2002), there is a lack of information on Mediterranean systems. In addition, estimates of SOC stocks may be particularly inaccurate in areas with diverse land use patterns, such as Mediterranean landscapes.

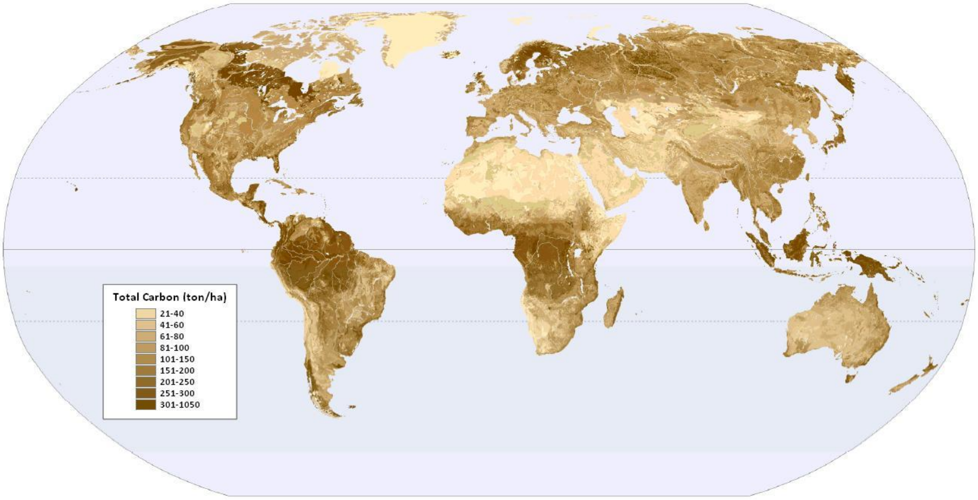


Figure 1.2. Global soil organic carbon pool. Source: adapted from Kapos et al., 2008.

At the same time, soil depth has an important influence on SOC stocks (Grüneberg et al., 2010). Most studies on SOC are restricted to the topsoil, and soil measurements are often taken in the upper layers, although vertical processes have a considerable effect on SOC variability (VandenBygaart, 2006). A significant amount of SOC can be stored in deeper layers and this form of C has proven to be more stable (Jobbagy and Jackson, 2000).The few existing studies that contrast the dynamics of SOC in the upper horizons and the subsurface, suggest a variation with depth in the factors that control the dynamics of SOC, an assumption that has not yet been investigated in detail (Albadalejo et al., 2011; Salome et al., 2010). Thus, vertical distribution is one of the features of the organic carbon pool that is not clearly understood together with the relationships with climate and vegetation (Jobbágy and Jackson, 2000). Nonetheless soil types differ in their properties and their capacity for C storage (Eswaran et al., 2003; Gamboa and Galicia, 2011) and SOC distribution with depth is expected to vary with different land cover and soil types (Schrumpf et al., 2008).

1.3.2 Measurement of soil organic carbon stocks and changes

Soil C monitoring methodologies are not yet well established since changes in soil C contents are slow, but a variety of methods for SOC assessments have been tested and developed in different countries (Ogle and Paustian, 2005; Post et al., 1999). However, efforts should be made to ensure that methodologies are comparable. Soil organic C measurement methods can be broadly classified into direct and indirect methods (Table 1.3), although most assessments usually involve a combination of these techniques. The scale and objective of a project determine the methods and data that should be used. However, the best methods to estimate changes in soil C pools over large geographical areas are the statistical analyses of repeated soil C content measurements based on spatially distributed soil samples (soil carbon monitoring), modeling or combinations of these two methods (Ravindranath and Oswald, 2008). To determine SOC stocks there are different methods, which include: (a) a flux approach (estimating all input and output soil C fluxes over a period of time), (b) repeated inventory and (c) determination of changes in specified fractions of C. Several studies have estimated SOC stocks on a large scale by using national and global soil spatial datasets and representative soil profiles, or by combining soil and land cover maps (Arrouays et al., 2001; Batjes, 1996; Batjes 2005; Batjes and Dijkshoorn, 1999; Bradley et al., 2005; Leifeld et al., 2005; Morisada et al., 2004). Frequently, inventories are based on a combination of soil-land use mapping units linked to mean SOC values from soil profiles.

Thus, it is possible to determine patterns in SOC variability related to soil and land use features. However, the consistency of these estimates depends upon the quality and resolution of the land use and soil spatial databases. In addition, because the large spatial variability of SOC within the map units, an elevated density of soil sampling points is required to reach accurate estimates (Liebens and VanMolle, 2003; Martin et al., 2011).

At European level, available information on spatial distribution of SOC contents is currently offered by the Joint Research Center (Jones et al., 2004). The European Topic Centre for Spatial information and Analysis, ETC/SIA, supports the European Environment Agency (EEA) and is developing a methodology for soil carbon accounting in Europe

Table 1.3. Methods for soil C measurement. Source: Kutsch et al., 2009; Smith, 2004

Measurement methods of soil carbon	Advantages	Disdvantages
Direct methods		
Field sampling and laboratory measurements (dry combustion or wet combustion)	Precise Transparent estimates that can be reported consistently over time Trend estimates can be verified with model-based estimates.	Laborious and expensive Time consuming Uncertainties because of high spatial variation of soil carbon
Eddy covariance; flux tower measurements	Minor disturbances to the soil structure	Difficulties in separating plant respiration from decomposition of dead soil organic carbon Insufficient geographical coverage of such measurements.
Emerging in situ methods: laser, infrared spectroscopy, etc.	Very fast Soil organic carbon can be distinguished from inorganic carbon	Expensive in the case of spectroscopy Methods in development.
Indirect method		
Accounting techniques (remot sensing)	Large coverage. It can provide highly accurate information for some types of carbon-related measures.	High fixed cost of providing remote coverage; satellites are very expensive to launch and maintain. Aircraft is less expensive but cover less area.
Modelling: RothC, Century, etc.	Fast Cost-effective; Results of validity tests in one country may be relevant for other countries. Can be used for estimating soil carbon pool in the past, present and future if input data are available (scenarios).	Soil carbon cycle may be inadequately described in the model: effects of factors that have an effect on soil carbon but not included in the model. Potential bias of the model difficult to estimate.

(Weber, 2011). Their method is based on CORINE land cover maps and remote sensing techniques. However further improvements are needed for land carbon accounting through more accurate data and the use of models and decision support system (DSS) tools.

1.3.3 Modelling soil organic carbon stocks

Main difficulties with soil carbon monitoring include the large amount of work needed and the consequently elevated costs. Additionally, the consistency between different monitoring rounds should be considered. Thus, combining modelling with monitoring can reduce the work and costs associated with this method. In general, models are efficient tools for a better understanding of the different processes involved in SOC dynamics.

They are used to extrapolate and interpolate experimental results in time, space and different environmental conditions. However, they are principally useful to investigate scenarios and hypotheses under different conditions (Christensen et al., 2011). Models are increasingly being used as DSSs, which are informatics structures that combine data and knowledge from different sources and evaluate information under different scenarios (Wang et al., 2010), helping to support complex decision-making and problem solving (Shim et al., 2002). Among DSSs, the MicroLEIS decision support system has been widely used in land evaluation (De la Rosa, 2004). MicroLEIS DSS was developed to assist decision-makers with specific agro-ecological problems. It has been designed as a knowledge-based approach which incorporates a set of information tools, linked to each other. Thus, custom applications can be performed on a wide variety of problems related to land productivity and land degradation. Table 1.4 shows a list of the MicroLEIS DSS models in two sets corresponding to i) land use planning, and ii) soil management planning.

Table 1.4. MicroLEIS DSS models. Source : De la Rosa et al., 2004

Model	Land evaluation issue	Modelling approach	Specific strategy supported
Albero	Agricultural soil productivity	Statistical	Quantification of crop yield: for wheat, maize, and cotton.
Alcor	Subsoil compaction and soil trafficability	Statistical	Site-adjusted soil tillage machinery: implement type, wheel load, and tire inflation.
Aljaraje	Soil plasticity and soil workability	Statistical	Identification of soil workability timing.
Almagra	Agricultural soil suitability	Qualitative	Diversification of crop rotation in best agricultural lands.
Arenal	General soil contamination	Expert system	Rationalization of total soil input application.
Cervatana	General land capability	Qualitative	Segregation of best agricultural and marginal agricultural lands.
ImpelERO	Erosion/impact/mitigation	Expert system/Neural network	Formulation of management practices: row spacing, residues treatment, operation sequence, number of implements, and implement type.
Marisma	Natural soil fertility	Qualitative	Identification of areas with soil fertility problems and accommodation of fertilizer needs.
Pantanal	Specific soil contamination	Expert system	Rationalization of specific soil input application: N and P fertilizers, urban wastes, and pesticides.
Raizal	Soil erosion risk	Expert system)	Identification of vulnerability areas with soil erosion problems.
Sierra	Forestry land suitability	Qualitative/Neural network	Restoration of semi-natural habitats in marginal agricultural lands: selection of forest species.
Terraza	Bioclimatic deficiency	Parametric	Crop water supply quantification and frost risk limitation.

In the last years, with the broad availability of computing systems with great capabilities, there is a growing tendency to use data mining (DM) techniques to complement or even replace process-based models (Figure 1.3). The term data mining is a part of a wider process named Knowledge Discovery from Data (KDD) by Fayyad et al. (1996), oriented to identify patterns in data sets. KDD includes several steps: collecting and cleaning the data, preprocessing, data reduction, and the application of specific algorithms to search for patterns in the data (data mining).

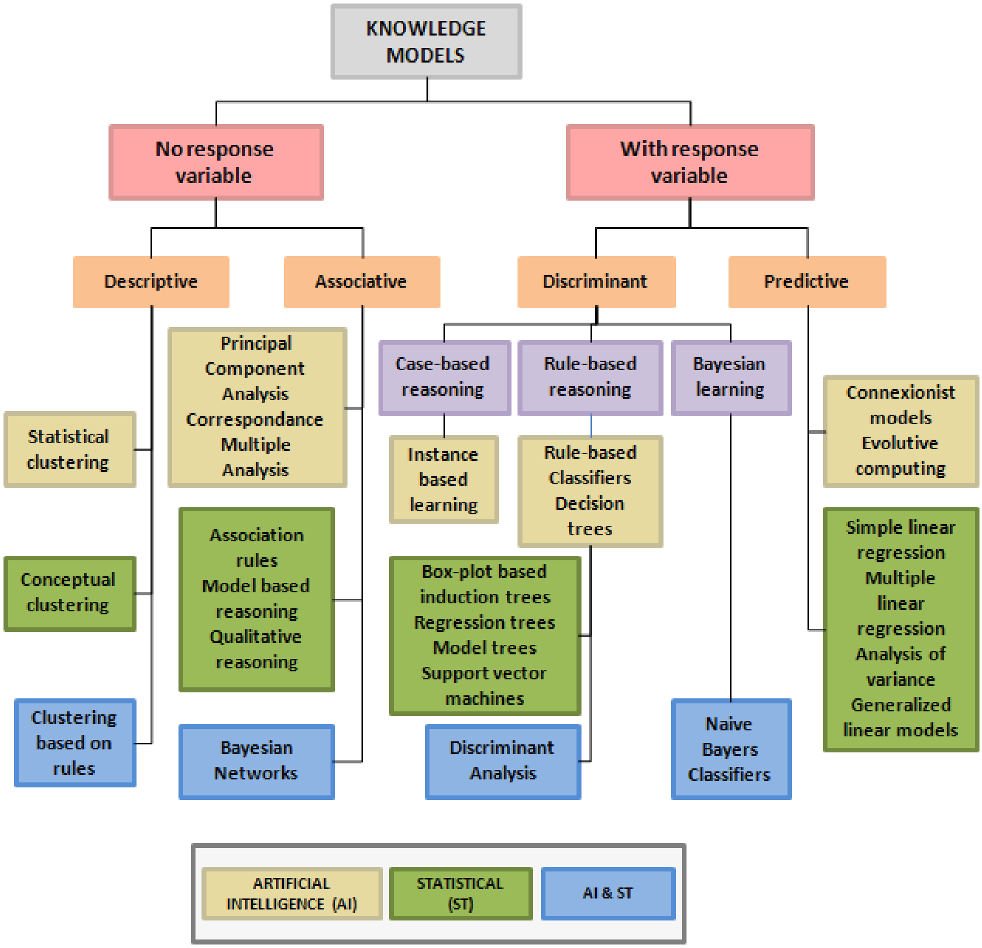


Figure 1.3. Data mining models types. Source: adapted from Gilbert et al., 2010

In large databases many relationships are possible and machine learning techniques are generally used to search this area of possibilities. Machine learning is concerned with the design and development of algorithms and techniques capable of learning from experience. There are a broad variety of methods used for modeling purposes, ranging from classic and simple statistical methods to sophisticated and computer-intensive techniques. However, the more complex data mining methods are not necessarily superior and simple models can yield a better performance for certain data sets. In land evaluation, statistical systems are potent empirical methods for land suitability prediction based on land characteristics. Correlation and multiple regression analyses have been used to investigate the contributions of selected land characteristics on land suitability and land vulnerability (De la Rosa et al., 2004). In soil C dynamics processes, empirical models based on regression/correlation techniques may not be able to explain complex mechanisms within the soil system but they can be useful tools to identify different drivers of SOC dynamics and perform projections of SOC stocks (Viaud et al., 2010).

Multiple Linear Regression (MLR) and Random Forest (RF), have been widely used in environmental modelling (Cutler et al., 2007; Pino et al., 2010; Syphard et al., 2008). MLR predicts the value of a quantitative variable as a linear equation of several numerical variables. It requires normality, linearity, homocedasticity and independence. Usually regression models are built with the goal of using the fewest predictors to explain the maximum variability in the response variable (Graham, 2003). Several approaches are available to select the most relevant predictors in regression models, such as stepwise procedures. Random Forest is a nonparametric technique derived from classification and regression trees. It consists of a combination of many trees, where each tree is generated by bootstrap samples, and approximately a third of the overall sample is left for validation. Each tree division is determined using a randomized subset of the predictors at each node and the final result is the average of the outputs of all the trees (Breiman, 2001; Cutler et al., 2007).

Regarding to SOC, models can be employed for SOC stocks and dynamics assessment at different scales, and they are able to predict soil C sequestration trends under different projected scenarios of land use or climate change (Kutsch et al., 2009). Simulation models describe changes in SOC under different conditions of climate, soil and management. Several soil C models have been developed in the last decades with different features and limitations (Table 1.5). Simulation models can be linked to spatial datasets (soil, land use, climate, etc.) to assess SOC dynamics related to different features and to determine current and future estimates of regional SOC stocks and SOC sequestration (Falloon et al., 1998; Hashimoto et al., 2012).

Table 1.5. Most commonly used soil carbon models.

Model	Input data	Otput data (C pools)	Spatial/ temporal scale	Depth	Limitations	Reference
CENTURY	T and total precipitation; plant N, P, and S content; soil texture; atmospheric and soil nitrogen inputs; and initial soil C, N and sulfur levels	Litter; SOM pools	m2/ years, month	20 cm	Only for top 20 cm	Parton et al. (1987)
EPIC	Daily air T and precipitation, radiation, texture, bulk density, C content.	Litter; SOM pools	Up to 100 ha/ years	From the topsoil (5cm) to 1m	More long-term studiesare needed for a	Williams (1990)
ROMUL	Litter; soil C in organic layer and in mineral layer;soil moisture;soil texture	Litter; SOM pools	m2/ month	Organic soil; 1 m mineral soil	Only for upland forest soils	Chertov et al. (2001)
ICBM	Enviornmental input to soil, humification coefficient; fraction of initial decomposition.	Young and old carbon	ha/ year	25 cm	Only two carbon pools (young and old carbon)	Andrén and Kätterer (1997)
DAYSY	Air T and precipitation; N input; texture; global radiation.	SOM pools	ha/ years, month	40 cm	Only agricultural soils	Müller et al. (1996)
RothC	Clay, monthly precipitation, monthly open pan evaporation, average monthly mean air T and an estimate of the organic input	Litter; SOM pools	ha/month	1 m	Only for upland forest soils	Coleman and Jenkinson (1995)
DNDC	Plant growth data, soil clay, bulk density, pH, air T, precipitation, atmospheric N decomposition rate, crop rotation timing and type, inorganic fertilizer timing, amount and type, irrigation timing and amount, residue incorporation timing and amount, and tillage timing and type.	Two layers with five pools: very labile litter, labile litter, resistant litter, humads	ha/ daily	50 cm	Complexity, too many inputs.	Li et al., 1994

In this context, Geographic Information System (GIS) technology provides a set of helpful tools and procedures to relate spatial data with soil C models. GIS technology stores, edits, analyzes, shares, and displays geographic information for informing decision making. One of the most widely used GIS software is ArcGIS from ESRI (2011). ArcGIS incorporates the ARcGIS Model Builder as a part of the Arc Toolbox of the ArcGIS system which allows to string together geoprocessing tools and Python scripts to build a new tool, such as a soil C model (Figure 1.4).

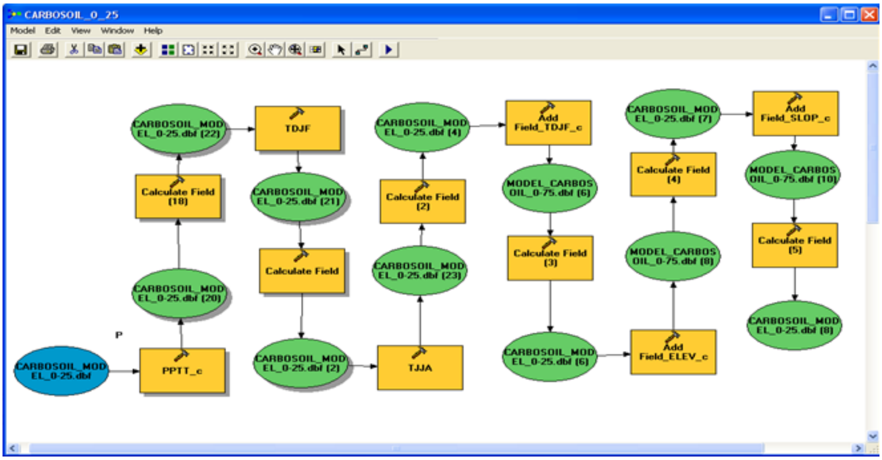


Figure 1.4. Model builder tool. ArcGIS software (ESRI). Example: CarboSOIL model application.

Model Builder is an intuitive, graphic workspace where new tools can be created by linking together different data layers and GIS analysis functions.

1.3.4 Climate change scenarios for soil carbon assessment

There is a growing interest in quantifying and understanding soil C stock changes over time, as a consequence of the rise in atmospheric CO_2 and the role of soils in C sequestration (Eaton et al., 2008; Smith, 2008; Wang et al., 2011). To predict future SOC stocks variations, Global Climate Models (GCMs) and Regional Climate Models (RCMs) are necessary to simulate global climate and produce projections of precipitation, temperature, and other climate variables (Lugato and Berti, 2008). Scenario analysis has been widely used for assessing future changes and projecting the consequences of climate change on different issues such as agriculture production, water and forest resources, etc.

The IPCC SRES (Special Report on Emissions Scenarios - SRES) scenarios were developed to study future developments in the global environment with special reference to the production of GHG emissions (IPCC, 2001; IPCC, 2007). These scenarios enclose different driving forces of climate change which consist of diverse future scenarios that might influence GHG sources and sinks, including the energy system and land use changes. Because of the large uncertainties concerning the evolution of these driving factors, there is a broad range of possible emissions paths of GHG. Thus, the IPCC SRES scenarios are divided in different storylines also called “families”, named A1, A2, B1 and B2, which represent different demographic, social, economic, technological, and environmental pathways (Mitchell et al., 2004; Nakicenovic et al., 2000). The A1 scenario assumes very rapid economic growth, a global population that reaches the highest point in mid-century and rapid introduction of new and more efficient technologies. Also, technology is assumed to be easily spread due to increased globalization. A1B is characterized by a balance across all energy sources. The A2 scenario entails a very heterogeneous world with high population growth, slow economic development and slow technological change. The B1 scenario assumes the same global population as A1, but with larger emphasis on sustainability and the B2 underlines local solutions to economic, social, and environmental sustainability (Figure 1.5).

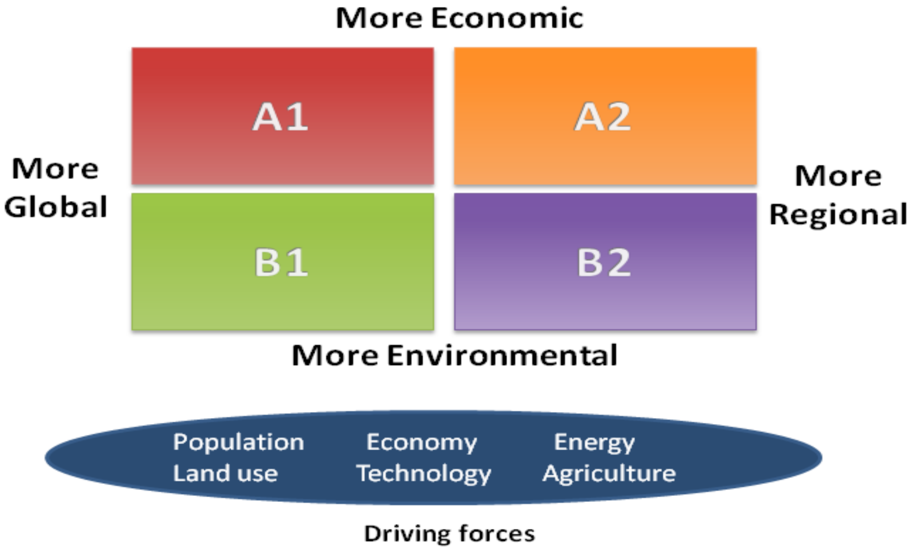


Figure 1.5. Future scenarios of the Intergovernmental Panel on Climate Change IPCC. Source: adapted from IPCC, 2007

Numerous research centers around the world have developed and used very sophisticated GCMs to simulate global climate (Table 1.6).

Table 1.6. Main Global Circulation Models.

Groups (country)	**Model(abr. name)**	**Horizontal resolution**	**Frequency of coupling**
Bjerknes Centre for Climate Research (Norway)	BCCR-BCM2.0 (BCM2)	1.9x1.9	1 day
Canadian Centre for Climate Modelling and Analysis (Canada)	cccma_cgcm3_1 _T63 (CGHR)	1.9x1.9	1 day
Météo-France / Centre National de Recherches Météorologiques (France)	CNRM-CM3 (CNCM3)	2.8x2.8	1 day
CSIRO Atmospheric Research (Australia)	CSIRO-Mk3.0 (CSMK3)	1.9x1.9	15 minutes
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group. (Germany / Korea)	ECHO-G (ECHOG)	3.9x3.9	1 day
LASG / Institute of Atmospheric Physics (China)	FGOALS-g1.0 (FGOALS)	2.8x2.8	1 day (ocean), 1 hour atmosphere.
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory (USA)	GFDL-CM2.0 (GFCM20)	2.5x2.0	2 hour (atmosphere-ocean)
NASA / Goddard Institute for Space Studies (USA)	GISS-ER (GIER)	4.0x5.0	30 minutes
Hadley Centre for Climate Prediction and Research /	UKMOHadCM3 (HADCM3)	3.75x2.5	1 day
Institute for Numerical Mathematics (Russia)	INM-CM3.0 (INCM3)	5.0x4.0	1 hour (atmosphere-sea-ice)
Instituto Nazionale di Geofisica e Vulcanologia (Italy)	INGV-SXG (INGSXG)	1.13x1.13	1.5 hours
Center for Climate System Research -The University of Tokyo (Japan)	MIROC3.2 (hires) (MIHR)	1.12x1.12	3 hours
Max Planck Institute for Meteorology (Germany)	MPI_ECHAM5 (MPEH5)	1.9x1.9	1 day (atmosphere and ocean-sea ice)
National Center for Atmospheric Research (USA)	NCAR_CCSM (NCCCSM)	1.4x1.4	1 day (ocean)1 hour (atmosphere-land ice)

Climate change is global in nature and, therefore, the starting point for the assessment is the GCMs. These models use the information on future GHG emissions from the socioeconomic scenarios and project the future changes in a range of climate parameters. Climate models, based on physical, chemical, and biological properties, and interactions and feedback processes, are numerical representations of the climate system.

They account for the known properties of the climate system and can be represented by models of varying complexity providing a comprehensive representation of the climate system (IPCC, 2007). It is important to understand how climate change affects at regional scales and studies involving RCMs are being developed. However, large differences remain between observations and model outputs (Buytaert et al., 2010). A different method to assess the impact of climate change at regional or local scales consist of using averages or weighted values based on statistical measures of model reliability, such as the correlation between observed and simulated climate patterns.

Applying Climate Models forced by IPCC SRES scenarios in SOC modeling allow us to investigate SOC changes in future climate scenarios. Climate change will affect SOC stocks and there is a need to predict the potential SOC stocks under different projections (Christensen et al., 2011). Thus, the combination of SOC models and climate change scenarios is a crucial instrument to support decision-making in land management and climate adaptation strategies.

1.4 Objectives

Global warming and climate change are major concerns nowadays. The role of terrestrial ecosystems as sources and sinks of C has been highlighted in the last years, underlining the impact of land cover changes on the C pools. Although Mediterranean areas show a high potential for C sequestration, few studies have been developed in Mediterranean systems. Carbon stock and changes in terrestrial C pools need to be assessed in response to international policies such as the Kyoto Protocol and to support environmental programs (e.g. the Millennium Ecosystem Assesment). The main objective of this thesis is to assess C dynamics in terrestrial ecosystems in Southern Spain and to develop a new model for C sequestration evaluation in Mediterranean soils. The specific objectives are the following:

- To investigate the dynamics of LULCCs at different levels of classification in southern Spain between 1956 and 2007 and to assess the temporal and spatial variability of C stored in vegetation during that period.
- To assess the influence of LULCCs between 1956 and 2007 on SOC stocks of representative Mediterranean soil types and to provide SOC sequestration rates for different LULCCs.
- To quantify current SOC stocks in southern Spain for each land use and soil type at different soil depths and to assess the relationships between SOC stocks and environmental variables.
- To build a model (CarboSOIL) for SOC stocks prediction in different scenarios of soil management, land use and climate change at different soil depths.
- To develop a computer based tool in a Geographical Information System (GIS) environment for spatial analysis of the inputs/outputs of the model CarboSOIL.
- To test and validate CarboSOIL model in climate change scenarios and to estimate SOC stocks in future climate projections for different land uses and soil types.

This research is part of a global project for developing a land evaluation tool for evaluating soil capacity for C sequestration, as a new component of the MicroLEIS Decision Support System (De la Rosa et al., 2004; De la Rosa, et al., 2009).

1.5 Research areas

The research of this thesis is developed in two representative areas of the Mediterranean region (Andalusia and Valencian region). The study area is Andalusia (southern Spain), which covers an area of approximately 87,000 km^2 (Figure 1.6).

Figure 1.6. Study area (Andalusia, southern Spain) and validation area (Valencia, eastern Spain).

Climate is mostly Mediterranean type, characterized mainly by the particular distribution of temperatures and precipitations. Annual rainfall decreases from western Atlantic areas to the eastern region, which has a dry Mediterranean climate and values ranging between 170 mm year^{-1} and > 2000 mm year^{-1}. Western Atlantic areas are more rainy and humid, while the eastern portion has a dry Mediterranean climate, almost desert. Average annual temperatures vary between <10 and 18 ^{o}C, although milder temperatures are observed at the coast. There is a large altitudinal range in Andalusia and elevation varies between 0 and 3,479 masl with the highest peak Mulhacén.

The typical soils of Andalusia compose an exceptional sample of the diversity of Mediterranean soils (De la Rosa, 1984). The main soils in the area are Cambisols (33%), Regosols (20%), Luvisols (13%) and Leptosols (11%) (CSIC-IARA, 1989).

Cambisols, in a continuous process of pedological maturation, are the most widespread soil reference group along the Mediterranean region. These soils, with moderate to deep soil profiles, are among the most productive in southern Europe. Regosols and Leptosols, typical of mountainous areas of the Mediterranean region are associated with eroding landscapes. They are weakly developed and have a low value for agriculture. Luvisols are well-developed fertile soils which are suitable for a broad variety of uses typically Mediterranean such as cereals, fruit trees, olives and vineyards (Zdruli et al., 2011).

Currently, approximately 43.9% of the region is occupied by agricultural areas and 50.8% by natural areas. Both urban and water spaces cover approximately 3% of the area respectively (Bermejo et al., 2011). Most of natural vegetation is Mediterranean forest, predominantly evergreen trees such as oaks, pines and firs, with dense riparian forests, and Mediterranean shrubland. Agriculture in Andalusia has traditionally been based on wheat crops, olive trees and vineyards but in recent decades, traditional crops have been substituted with intensive and extensive crops (e.g., wheat, rice, sugar beet, cotton and sunflower).

The validation area for the model development (Chapter 5) is the Valencian region, located on the eastern coast of Spain with an area of 23,259 km^2 (Figure 1.6). It constitutes the western boundary of the Mediterranean basin and its orography is rather complex. The highest peak is Peñagolosa (1815 masl), located in the northern part of the region. Regional climate is typically Mediterranean semiarid with an average annual precipitation between 300 and 500 mm (Peñarrocha, 1994; Millán et al., 2005). Warm temperatures prevail during most of the year with mean winter temperatures between 4 and 11 °C, and mean summer temperatures between 20 and 26 °C. Most of the area is covered by Mediterranean crops, with predominance of citrus orchards and vegetables.

The Mediterranean region has been exposed to intensive processes of land use/land cover changes in the last 50 years, with transformations from traditional agriculture to industrial and tourism economies altering the composition and spatial structure of the landscape (Figure 1.7 and Figure 1.8). Intensive greenhouse crops under plastic have spread through some areas. In the coastal area, the decline of traditional crops has been imposed mainly by massive urbanization and the development of tourist infrastructures (Bermejo et al., 2011).

Figure 1.7. Land cover changes in the Guadalquivir basin, western Andalusia (1956-2007). Source: Ortofotografía Digital Histórica de Andalucía. Junta de Andalucia.

Figure 1.8. Land cover changes in southeastern Andalusia (1956-2007). Source: Ortofotografía Digital Histórica de Andalucía. Junta de Andalucia.

CHAPTER 2

CHANGES IN LAND COVER AND VEGETATION CARBON STOCKS IN ANDALUSIA, SOUTHERN SPAIN (1956 – 2007)

2.1 Introduction

Global land use has significantly changed during the recent decades. At a global scale, population growth can be considered the main historical cause for land use change (Ramankutty et al., 2002), although different interactions and processes can be also considered at more detailed scales (Lambin et al., 2001). In developed countries, land use change is forced by economic reasons such as farming or urban development and associated processes, but also an increasing need to conserve biodiversity and environmental quality in the context of global change (Bouma et al., 1998). Global warming and climate change are major environmental concerns and are considered a consequence of anthropogenic emissions of carbon dioxide (CO_2). Concerns about the effects of LULCC were stressed during the second half of the 20th century, after the scientific community observed land surface processes can influence climate. The role of terrestrial ecosystems as sources and sinks of C has been highlighted, underscoring the impact of land cover changes on the global climate (Freibauer et al., 2004; Houghton et al., 1985; Milne and Brown, 1997; Woodwell et al., 1983). Based on various potential scenarios, it has been predicted that air temperature in 2100 will be increased in 1.8 - 4.0 ^{o}C, on average, considering the best estimate (IPCC, 2007). In addition, the Earth Systems Research Laboratory / National Oceanic and Atmospheric Administration (ESRL/NOAA) estimated that atmospheric concentration of CO2 for February 2011 increased up to 391.76 ppm (ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_mm_mlo.txt, accesed 10 March 2011) and levels will continue rising by about 1.9 ppm/yr on a year-over-year basis because CO_2 emissions from anthropogenic sources currently exceed the capacity of absorption of the terrestrial ecosystems and oceans.

Carbon is exchanged naturally between terrestrial aboveground and belowground C stocks and the atmosphere through chemical, physical, geological, and biological processes, although anthropogenic activities affect these fluxes between the different C pools. Soil organic carbon (OC) is considered the largest C stock in most terrestrial ecosystems, well above the C pool in plants (Eswaran et al., 2000; Jobbagy and Jackson, 2000). OC may take centuries to accumulate in soil, but LULCC can accelerate decomposition and abiotic processes (disturbance, erosion) resulting in increased C loss rates which are extremely difficult to reverse in the short term (Ostle et al., 2009; Post, 2000). The balance of the exchanges between these pools can provide information about whether the pool or reservoir is functioning as a source or sink for carbon dioxide (Erb, 2004).

The Kyoto Protocol to the United Nations Framework Convention on Climate Change requires national governments to assess and report national atmospheric C emissions and removals reflected as stock changes. Therefore, C stocks and changes in above and belowground C pools need to be quantified accurately (Johnson and Kerns, 2002). LULCC have effects on C stocks in soils and vegetation, contributing to climate change (Eaton et al., 2008; Schulp et al, 2008; Smith, 2008; Ostle et al., 2009). At a global scale, LULCC is estimated to contribute with 25% of the anthropogenic flux of carbon dioxide to the atmosphere, just after fossil fuels (Houghton et al., 1999; Houghton et al., 2001). The amount of C released to the atmosphere after LULCC is estimated as 1.6 ± 0.8 106 Mg year^{-1} (IPCC, 2007); however reducing CO_2 emissions and increasing C sequestration by vegetation and soils can contribute to decrease this rate (Cruickshank et al., 2000; Lal, 2004).

Land use spatial databases are a key source of information for natural resource management and planning. Many LULCC studies have provided valuable information for large-scale vegetation biomass, a major component of the C cycle, allowing us to acquire accurate knowledge of C storage in vegetation. Since the Kyoto Protocol was enunciated, changes in C pools due to LULCC have been evaluated, but it has been a primary challenge to quantify the storage of C induced by land cover change and the spatial and temporal dynamics of C sources and sinks at local, regional and global scales. This is mainly due to the lack of detailed land cover change databases and appropriate models (Watson et al., 2000, Lal et al., 2001; Zhao et al., 2010). However, after the development of remote sensing technologies and geographical information systems, reliable land cover information has been achieved and became available (Herold, 2006).

The main goal of this research is to investigate the dynamics of LULCCs at different levels of classification in Andalusia (S Spain) between 1956 and 2007 and to assess the temporal and spatial variability of C stored in vegetation during that period. According to this goal, the specific objectives of this work are to study [1] the changes in land cover, [2] the direction of changes of land cover types, [3] the vegetation C stocks and dynamics at different levels of classification, [4] the spatial distribution of vegetation C stocks, sinks and sources and [5] to outline the main implications for C stock dynamics. The information generated in this study will be a useful basis for designing management strategies for stabilising the increasing atmospheric CO_2 concentrations by preservation of C stocks and C sequestration.

2.2 Materials and methods

2.2.1 Classification of land use and land cover

The land use classification for this study is derived from the Land Use and Land Cover Map of Andalusia (LULCMA; Moreira, 2007) for the period 1956 and 2007 at scale 1:25,000 and minimum map unit 0.5 ha. The LULCMA maps for 1956 and 2007 were carried out by the Andalusian Regional Ministry of Environment (ARME; Moreira, 2007). The LULCMA map for 1956 was produced by photo-interpretation of 1956 B/W aerial photographs with spatial resolution 1 m. The LULCMA map for 2007 was produced after photo-interpretation of 2007 color aerial photographs (spatial resolution 1 m), infra-red ortophotos (spatial resolution 0.5 m) and satellite imagery (Landsat TM, IRS/PAN and SPOT-5). The orthorectification process of 1956 imagery was addressed by the ARME using more than 8000 scanned frames.

These maps are a result of the Coordination of Information on the Environment programme (CORINE) promoted by the European Commission in 1985 for the assessment of environmental quality in Europe. Within the CORINE programme, the CORINE Land Cover (CLC) project provides consistent information on land cover and land cover changes across Europe (Neumann et al., 2007). Land Cover Maps provide an updated version of the original maps at scale 1:100000 and constitute more detailed and accurate databases, both thematically and geometrically. LULCMA land cover maps are divided in 166 classes, derived from original CORINE 44 classes. In this research, and for generalization purposes, land cover classes of LULCMA were reclassified into CLC standard nomenclatures, in order to make methodology available for other countries member of the CORINE program and get easily comparable results. Table 2.1 shows the reclassification of LULCMA land cover classes into CLC nomenclature. The standard CLC nomenclature includes 44 land cover classes, grouped in a three-level hierarchy. The five main classes (level 1) describe land patterns for use on a planet scale, comprising the following categories: 1) “Artificial surfaces”, 2) “Agricultural areas”, 3) “Forests and semi-natural areas”, 4) “Wetlands”, and 5) “Water bodies” (Heymann et al., 1994). Level 2 (15 classes) corresponds to the physical and physiognomic entities at scales 1:500,000 and 1:000,000 (“Urban zones”, “Forests”, “Lakes”, etc); finally, level 3 is composed of acutely defined 44 classes for use on scale 1:100000 and higher (“Residential areas”, “Airport”, “Commercial areas”, etc.). All national working groups adopted this standard nomenclature, although it has been improved over the years by introducing local subclasses.

2.2.2 Land cover change detection

The methodology applied for LCC analysis is based on results reported by Feranec et al. (2010) (i.e. LCFs defined on the second level of CLC legend). The derivation of LCFs has been carried out using conversion tables which groups similar LC changes. There are 210 possible combinations of changes between the 15 CLC classes, which were described by Feranec et al. (2010) as follows: 1) “Urbanization”: this flow represents the change of agricultural (classes 21, 22 and 23), forest land (classes 31, 32 and 33), wetlands (classes

Table 2.1. Reclassification of Andalusia land cover classes into CORINE LAND COVER (CLC) nomenclature.

CORINE land cover				**Land use and land cover map of andalucia**	
Level1	**Level 2**	**Level 3**		**Level 3**	
1	Artificial surfaces				
	11	Urban fabric			
		111	Continuous Urban Fabric	111	Continuous Urban Fabric
		112	Discontinuous Urban Fabric	115	Residential Urbanisation
				117	Agricultural and residential urbanisation
	12	Industrial, commercial and transport units			
		121	Industrial or commercial units	121	Industrial or commercial units
				141	Other technical infrastructures
		122	Road and rail networks and associated land	131	Roads
				133	Rail networks
		123	Port areas	135	Port areas
		124	Airports	137	Airports
	13	Mine, dump and construction sites			
		131	Mineral extraction sites	151	Mineral extraction sites
		132	Dump sites	153	Dump sites
				157	Olive-mill waste water pools
				345	Irrigation pool
		133	Construction sites	155	Construction sites
	14	Artificial, non-agricultural vegetated areas			
		141	Green urban area	191	Green urban area
		142	Sport and leisure facilities	193	Sport and leisure facilities
2	Agricultural areas				
	21	Arable land			
		211	Non-irrigated arable land	411	Non-irrigated arable land
		212	Permanently irrigated land	423	Crops under plastic
				425	Irrigated land: other irrigated crops
				427	Irrigated land: irrigated and non-irrigated
				429	Irrigated land: non-irrigated
		213	Rice fields	421	Rice fields
	22	Permanent crops			
		221	Vineyards	417	Non-irrigated woody crops: vineyards
		222	Fruit trees and berry plantations	419	Non-irrigated woody crops: other crops
				430	Irrigated woody crops: partially or non-irrigated
				431	Irrigated woody crops: citrus fruits
				435	Irrigated woody crops: tropical fruits
				439	Irrigated woody crops: other crops
				489	Irrigated woody crops: abandoned crops
		223	Olive grooves	415	Non-irrigated woody crops: olive grooves
				433	Irrigated woody crops: olive trees
				481	Abandoned olive trees
	23	Pastures			
		231	Pastures		
	24	Heterogeneous agricultural areas			
		241	Annual crops associated with permanent crops	441	Non-irrigated herbaceous and woody crops
		242	Complex cultivation patterns	445	Non-irrigated woody crops: olive grove-vineyard
				449	Non-irrigated woody crops mosaic: other crops
				451	Irrigated herbaceous and woody crops
				455	Partially Irrigated herbaceous and woody crops
				457	Irrigated herbaceous and woody crops: non-irrigated
				459	Irrigation woody crops mosaic
				461	Irrigation woody crops with herbaceous mosaic
				465	Irrigation woody crops with herbaceous and woody crops mosaic
				469	Irrigation woody crops with woody crops mosaic
		243	Land principally occupied by agriculture, with significant areas of natural vegetation	471	Herbaceous and pastures
				473	Herbaceous and natural woody vegetation
				475	Woody crops and pastures
				477	Woody crops and natural woody vegetation
				479	Crops and natural vegetation mosaic: other crops
		244	Agro-forestries areas	811	Wooded pasture: dense Quercus
				815	Wooded pasture: scattered Quercus
				891	Wooded herbaceous crops: dense Quercus
				895	Wooded herbaceous crops: scattered Quercus

Table 2.1. Continued.

CORINE land cover				**Land use and land cover map of andalucia**	
Level1	**Level 2**	**Level 3**		**Level 3**	
3	Forest and semi-natural areas				
	31	Forests			
		311	Broad-leaved forests	315	Rivers and natural beds: gallery forest
				317	Rivers and natural beds: other riparian formations
				510	Dense wooded formation: Quercus
				530	Dense wooded formation: Eucalyptus
				540	Dense wooded formation: other broad-leaved forests
				611	Dense wooded shrub: dense Quercus forest
				630	Dense wooded shrub: Eucalyptus
				640	Dense wooded shrub: other broad-leaved forest
				711	Scattered wooded shrubs: dense Quercus
				730	Scattered wooded shrubs: Eucalyptus
				740	Scattered wooded shrubs: other broad-leaved forests
				830	Wooded pasture: Eucalyptus
				840	Wooded pasture: other broad-leaved forests
		312	Coniferous forests	520	Dense wooded formation: conifers
				621	Dense wooded shrub: dense conifers
				721	Scattered wooded shrub: dense conifers
				821	Wooded pasture: dense conifers
		313	Mixed forests	550	Dense wooded formation: Quercus and conifers
				560	Dense wooded formation: Quercus and Eucalyptus
				570	Dense wooded formation: conifers and Eucalyptus
				580	Dense wooded formation: other mixtures
				650	Dense wooded shrub: Quercus and conifers
				660	Dense wooded shrub: Quercus and Eucalyptus
				670	Dense wooded shrub: conifers and Eucalyptus
				680	Dense wooded shrub: other mixtures
				750	Scattered wooded shrub: Quercus and conifers
				760	Scattered wooded shrub: Quercus and Eucalyptus
				770	Scattered wooded shrub: conifers and Eucalyptus
				780	Scattered wooded shrub: other mixtures
				850	Wooded pasture: Quercus and conifers
				860	Wooded pasture: Quercus and Eucalyptus
				870	Wooded pasture: conifers and Eucalyptus
				880	Wooded pasture: other mixtures
	32	Scrub and/or herbaceous vegetation associations			
		321	Natural grasslands	921	Continuous pasture
				925	Pastures with bare rock
		323	Sclerophyllous vegetation	911	Dense shrub
				915	Scattered shrub with pasture
				917	Scattered shrub with pasture and bare rock
		324	Transitional woodland-scrub	615	Dense wooded shrub: scattered Quercus
				625	Dense wooded shrub: closed Quercus
				715	Scattered wooded shrub: scattered Quercus
				725	Scattered wooded shrub: scattered Conifer
				825	Wooded pasture: scattered Conifer
				901	Deforestation and recent afforestation
				935	Areas without vegetation- ploughing
	33	Open spaces with little or no vegetation			
		331	Beaches, dunes and sand	931	Beaches, dunes and sand
		332	Bare rocks	932	Bare rocks
		333	Sparsely vegetated areas	933	Erosive processes areas
		334	Burnt areas	934	Burnt areas
		335	Glaciers and perpetual snow		
4	Wetlands				
	42	Maritime wetlands			
		421	Salt marshes	211	Coastal salt marshes with vegetation
				215	Inland salt marshes with vegetation
				217	Fresh salt marshes without vegetation
		422	Salines	221	Traditional salines
				225	Industrial salines and crop parks
5	Water bodies				
	51	Inland waters			
		511	Water courses	311	Rivers and natural beds: water bodies
		512	Water bodies	321	Artificial channels
				341	Reservoir: water bodies
	52	Marine waters			
		521	Coastal lagoons	331	Coastal lagoons
		522	Estuaries	241	Estuaries and tidal channels
		523	Sea and ocean	291	Seas and oceans

41 and 42) and water bodies (51 and 52) into urbanized and industrialized land; 2) “Intensification of agriculture”: it involves the transition of LC types associated with lower intensity use (e.g. classes 32, 33 from the natural area, and wetland) into higher intensity uses; 3) “Extensification of agriculture”: it represents the transition of LC types associated with a higher intensity use (classes 21 and 22) to the lower intensity use (classes 23 and

24); 4) “Afforestation”: this flow represents forest regeneration - the establishment of forests through new plantations and/or natural regeneration (change of classes 21, 22, 23, 24, 33, 41 and 42 into classes 31 and 32); 5) “Deforestation”: a flow which represents the transition of forest land (class 31) into agricultural or damaged forest (classes 21, 22, 23, 24, 32 and 33); 6) “Water bodies construction and management”: change of agricultural classes (classes 21, 22, 23 and 24) and forest land (classes 31 and 32) into water bodies; and 7) “Other changes”, which was not considered for this study. In this research, LC changes between 1956 and 2007 were detected by comparison of the LULCMA data layers from 1956 and 2007. The classes of the land LCC databases were reclassified into 7 types of LCFs according to Table 2.2. Systematic transitions among classes were calculated using PASW Statistics 18.0 for Windows (SPSS Inc., 2009) and spatial analysis techniques included in the ArcGIS 9.2 software pack (ESRI, 2006).

Table 2.2 Derivation of the main LCFs for the second level of CLC classes (as in Feranec et al., 2010).
CLC classes: 11, urban fabric; 12, industrial, commercial and transport units; 13, mine, dump and constructions sites; 14, artificial, non-agricultural vegetated areas; 21, arable land; 22, permanent crops; 24, heterogeneous agricultural areas; 31, forests; 32, scrub and/or herbaceous vegetation associations; 33, open spaces with little or no vegetation; 41, inland wetlands; 51, inland waters; 52, marine waters. LCF codes: 1-Urbanisation, 2-Intensification of agriculture, 3-Extensification of agriculture, 4-Afforestation, 5-Deforestation, 6-Water bodies construction and management, 7-Other changes (recultivation, dump sites, unclassified changes, etc.).

1956 classes	**2007 classes**														
	11	**12**	**13**	**14**	**21**	**22**	**23**	**24**	**31**	**32**	**33**	**41**	**42**	**51**	**52**
11	0	7	7	7	7	7	7	7	7	7	7	7	7	7	7
12	7	0	7	7	7	7	7	7	7	7	7	7	7	7	7
13	7	7	0	7	7	7	7	7	7	7	7	7	7	6	7
14	7	7	7	0	7	7	7	7	7	7	7	7	7	6	7
21	1	1	1	1	0	2	3	3	4	4	7	7	7	6	7
22	1	1	1	1	3	0	3	3	4	4	7	7	7	6	7
23	1	1	1	1	2	2	0	2	4	4	7	7	7	6	7
24	1	1	1	1	2	2	3	0	4	4	7	7	7	6	7
31	1	1	1	1	5	5	5	5	0	5	5	5	7	6	7
32	1	1	1	1	2	2	2	2	4	0	5	7	7	6	7
33	1	1	1	1	2	2	2	2	4	4	0	7	7	6	7
41	1	1	1	1	2	2	2	2	4	4	7	0	7	6	7
42	1	1	1	1	2	2	2	2	4	4	7	7	0	6	7
51	1	1	1	1	7	7	7	7	4	4	7	7	7	0	7
52	1	1	1	1	7	7	7	7	4	4	7	7	7	7	0

2.2.3 Carbon stocks in vegetation and spatial distribution

To estimate C vegetation stocks and spatial distribution of C in vegetation, C vegetation densities were associated to land cover types. For each CLC class at level 3, C vegetation density data were derived from literature (Cruickshank et al. 2000; Pereira et al. 2009), as shown in Table 2.3 with values respecting the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (Houghton et al., 2001; IPPC, 2007). These values take into account stems, branches, foliage and roots (aboveground and belowground biomass), but do not include litter, microbial biomass and soil OC. Carbon vegetation stocks for 1956 and

Table 2.3. Carbon vegetation density for each CLC class at Level 3 of nomenclature, according to Cruickshank et al. (2000) and Pereira et al. (2009).

Class	CLC Nomenclature	C density ($Mg{\cdot}ha^{-1}$)	Description
111	Continuous Urban Fabric	0.00	Assumed equal to continuous urban fabric in Ireland: no vegetation cover.
112	Discontinuous Urban Fabric	3.23	Assumed equal to disc. Urban fabric, warm temperature: intermediate value between continuous urban fabric and gardens.
121	Industrial or commercial units	0.00	Assumed equal to industrial/commercial units in Ireland: no vegetation cover.
122	Road and rail networks and associated land	0.00	Assumed equal to road and rail networks and associated land in Ireland: no vegetation cover.
123	Port areas	0.00	Assumed equal to port areas in Ireland: no vegetation cover.
124	Airports	0.50	Assumed equal to airports: 50% built surfaces and 50% grass.
131	Mineral extraction sites	0.00	Assumed equal to mineral extraction sites in Ireland: no vegetation cover.
132	Dump sites	0.00	Assumed equal to dump sites in Ireland: no vegetation cover.
133	Construction sites	0.00	Assumed equal to construction sites in Ireland: no vegetation cover.
141	Green urban areas	6.46	Assumed equal to gardens, parks, etc. Warm temperature.
142	Sport and leisure facilities	6.46	Assumed to be equal to gardens, parks, etc. Warm temperature.
211	Non-irrigated arable land	5.00	Assumed equal to annual cropland.
212	Permanently irrigated land	5.00	Assumed equal to annual cropland.
213	Rice fields	5.00	Assumed equal to annual cropland.
221	Vineyards	21.00	Assumed equal to permanent crops. Temperate (all moisture regimes). Assuming 10 years average.
222	Fruit trees and berry plantations	21.00	Assumed equal to permanent crops. Temperate (all moisture regimes). Assuming 10 years average.
223	Olive groves	21.00	Assumed equal to permanent crops. Temperate (all moisture regimes). Assuming 10 years average.
231	Pastures		Not applied.
241	Annual crops associated with permanent crops	13.00	Assumed equal to 50% annual crops and 50 % permanent crops.
242	Complex cultivation patterns	11.52	Assumed equal to mosaic agriculture with all other types: sum of biomass in forest/undercover (10%), bush land (10%) and annual cropland (80%).

2007 were calculated by multiplying C density for each land cover class with land cover areas. The spatial distribution of vegetation C stock for each class was mapped.

2.3. Results

2.3.1 Land cover changes in Andalusia between 1956-2007

The area affected by LCCs in Andalusia, identified using LULUCMA 1956-2007, was 29480 km^2 representing 33.6% of the total studied area (Table 2.4). Major changes include transformation from forest to agricultural areas (3476 km^2, 7.7 % of forest areas in 1956), agricultural to forest areas (2556 km^2, 6.6 % of agricultural areas in 1956) and agricultural to urban areas (1533 km^2, 3.9 % of agricultural areas in 1956) (Table 2.5).

Other significant transformations are those from urban areas to agriculture or forest areas (45.4 km^2, 8.8 % of urban areas in 1956) and a great decrease of water bodies mainly due to desiccation of wetlands (265 km^2, 9.1 % of ponded areas in 1956). Approximately 20.7 % of ponded area in 1956 was transformed to agricultural (501 km^2, 17.2 %) and forest areas (101 km^2, 3.5 %).

Table 2.4. Area affected by land cover changes in Andalusia, vegetation carbon sinks and sources according to LCFs (positive values indicate sequestration), and variation of vegetation carbon density (mean ± SD) for the period 1956-2007.

Land Cover Flow	Area km^2	Area %	Vegetation carbon sink/source Tg	Mean variation of vegetation carbon density Mg ha^{-1}
No change	58130.1	66.4	1.75	0.30 ± 6.30
Urbanization	2168.9	2.5	-2.57	-12.25 ±9.92
Intensification of Agriculture	9815.4	11.2	8.14	7.44 ± 10.66
Extensification of Agriculture	5039.1	5.8	-1.58	-9.59 ± 9.25
Afforestation	8919.5	10.2	17.73	17.34 ± 18.24
Deforestation	2934.5	3.3	-5.60	-18.93 ±14.41
Construction of Water Bodies	408.8	0.5	-0.63	-14.75 ± 9.72
Other changes	194.0	0.2	0.00	-0.85 ± 12.26
Total	87610.3	100	17.24	1.30 ± 14.27

Table 2.5. Land cover changes in Andalusia for the period 1956-2007. Contingency table at CLC Level 2 of nomenclature. CLC classes: 11, urban fabric; 12, industrial, commercial and transport units; 13, mine, dump and constructions sites; 14, artificial, non-agricultural vegetated areas; 21, arable land; 22, permanent crops; 24, heterogeneous agricultural areas; 31, forests; 32, scrub and/or herbaceous vegetation associations; 33, open spaces with little or no vegetation; 41, inland wetlands; 51, inland waters; 52, marine waters.

Land cover classes (1956)	**Land cover classes (2007)**													**Total (1956)**	
	11	**12**	**13**	**14**	**21**	**22**	**24**	**31**	**32**	**33**	**41**	**51**	**52**	**Area (km^2)**	**Area %**
11	341.3	1.5	0.8	0.4	3.5	1.4	0.4	0.5	1.5	0.1	0.0	0.3	0.0	351.7	0.4
12	3.5	57.5	1.6	0.3	15.7	2.0	0.5	5.1	6.5	0.5	0.0	0.2	0.0	93.4	0.1
13	9.5	4.2	37.0	1.7	1.3	0.3	0.2	2.0	4.0	0.0	0.0	1.1	0.0	61.3	0.1
14	0.5	0.1	0.0	5.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.5	0.0
21	357.4	226.9	193.5	32.1	10932.3	5082.9	2745.1	233.5	873.8	26.2	2.3	88.7	0.4	20795.1	23.8
22	214.2	108.3	112.5	14.5	1885.2	10131.3	408.8	87.9	308.6	18.3	0.1	34.2	0.0	13323.9	15.2
24	192.2	48.3	51.5	7.2	598.4	913.6	6682.9	938.7	1004.1	20.5	0.3	41.9	0.0	10499.5	12.0
31	51.2	22.1	41.9	9.9	448.5	268.4	681.6	12127.4	1232.5	70.7	0.1	116.7	0.0	15070.9	17.2
32	137.0	84.9	193.3	25.6	1.099.9	827.5	866.0	5354.9	16598.3	233.0	3.4	100.5	0.4	25524.7	29.2
33	9.2	2.3	1.3	0.7	2.4	2.5	1.4	16.2	27.4	199.9	0.4	5.6	3.0	272.2	0.3
41	2.1	8.1	6.9	0.8	386.9	1.6	32.2	10.6	27.6	2.7	690.1	20.1	6.5	1196.2	1.4
51	0.4	1.6	1.3	0.5	12.9	2.2	1.7	15.8	18.0	10.1	3.6	253.7	0.4	322.4	0.4
52	0.6	8.3	0.3	0.1	0.3	0.0	0.0	0.0	2.3	6.8	0.8	0.5	7.9	28.1	0.0
Area (km^2)	1319.1	574.0	641.9	99.6	15387.5	17233.6	11420.9	18792.7	20104.6	588.7	701.1	663.5	18.6	87545.7	100.0
Area %	1.5	0.7	0.7	0.1	17.6	19.7	13.0	21.5	23.0	0.7	0.8	0.8	0.0	100.0	

In detail, the most important LCC during the period 1956-2007 was "intensification of agriculture" which accounts for 11.2% of the total area and 9815.4 km^2. The second major change was "afforestation", which affected 8919.5 km^2 (10.2 % of the total area). "Extensification of agriculture" involved 5.8% of the total area and 5039.1 km^2. The remaining types of change ("deforestation", "urbanization", "construction of water bodies" and "other changes") covered 6.5 % of the total area. Major LULCCs in Southern Spain between 1956 and 2007 are shown in Figure 2.1. The main LC types in Andalusia included "scrub and herbaceous vegetation associations", "forests", "permanent crops" and "arable land" (Table 2.5).

"Scrub and herbaceous vegetation associations" covered about 25524.7 km^2 (29.2% of the studied area in 1956). In the next 51 years this LC type showed the largest decline by 5420.1 km^2 (23.0% in 2007). This was partly due to the conversion of 5354.9 km^2 of this land cover type into "forests", and 1100 km^2 into "arable land". The area occupied by "forests" increased by 4.3% covering more than 18792.7 km^2 (21.5% of the study area in 2007). A forest area of 2943.5 km^2 was converted mainly to "scrub and herbaceous vegetation associations" and "heterogeneous agricultural areas".

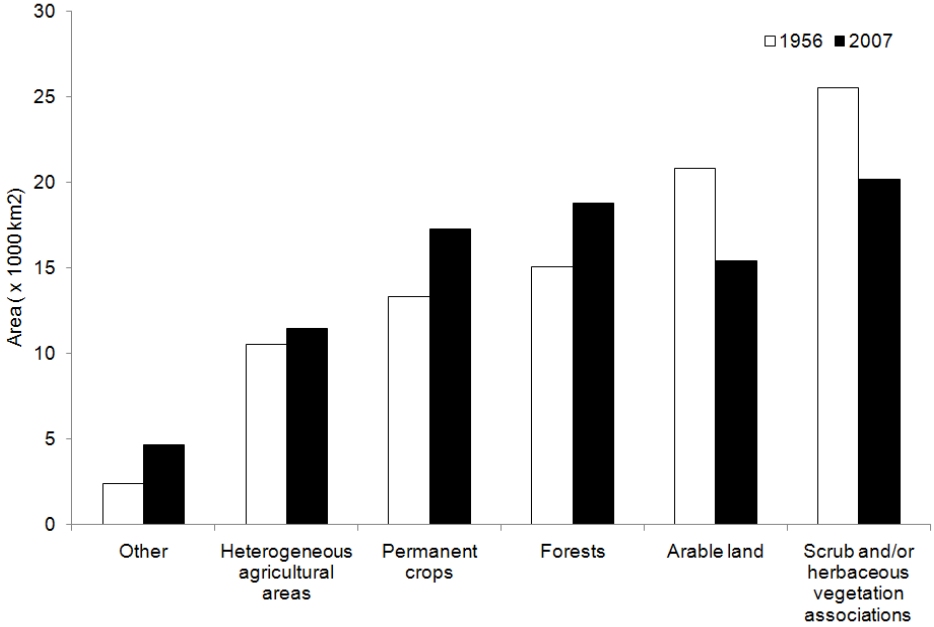


Figure 2.1. Land use and land cover changes (ULCCs) in Andalusia between 1956 and 2007 at CLC level 2.

Nevertheless, “forests” regained 6665.3 km^2 from “scrub and herbaceous vegetation associations”, “heterogeneous agricultural areas” and “arable land”, which resulted in a total increase of 3721.8 km^2 from 1956 to 2007. Meanwhile, the area dedicated to “permanent crops” increased from 13323.9 km^2 in 1956 to 17233.6 km^2 in 2007, mainly due to conversion from “arable land" (5082.9 km^2), “heterogeneous agricultural areas” (913.6 km^2), “scrub and/or herbaceous vegetation associations” (827.5 km^2) and “forests” (268.4 km^2). On the contrary, “arable land” decreased by 6.2% from 1956, resulting in a total area of 15387.5 km^2 (17.6% of the study area).

2.3.2 Vegetation carbon dynamics in Andalusia between 1956-2007

Table 2.4 shows the variation of vegetation carbon density for the studied LCFs between 1956 and 2007. The increase in urban areas between 1956 and 2007 resulted in a loss of 2.57 Tg C vegetation. “Intensification of agriculture” contributed to a sequestration of 8.14 Tg C in vegetation between 1956 and 2007. In contrast, “extensification of agriculture” involved a C loss of 1.58 Tg. “Afforestation” extended the amount of C stored in the vegetation contributing with 17.73 Tg. More than 3.3% of the total area of Andalusia corresponds to “deforestation”, resulting in a total loss of 5.60 Tg C in vegetation. In addition, the area of water bodies increased in Andalusia by 4087 ha, which translates in a total C loss of vegetation of 0.63 Tg. Distribution of the vegetation C density (Mg C ha^{-1}) and vegetation C balance between 1956 and 2007 in Andalusia is shown in Figure 2.2.

The difference between vegetation C stocks in 1956 and 2007 is shown in Table 2.6. LCCs between 1956 and 2007 have originated a vegetation C sink of 17.24 Tg which translates into sequestration of 338.04 10^{-3} Mg C ha^{-1} yr^{-1}. The total vegetation C stocks estimated in Andalusia were 138.8 Tg in 1956 and 156.1 Tg in 2007. Positive vegetation C stock values indicate sinks while negative values indicate sources of vegetation C. The area of coniferous forest has doubled in 51 years (1956-2007) resulting in a total C stock of 32.20 Tg in 2007 (Table 2.6). The contribution of this forest type to total vegetation C sinks (20.63%) is the largest among the LC classes. In total, forests comprise 32.2 % of the total vegetation C stock in 14.1 % of the study area in 1956 and 41.1 % of total vegetation C stock in 18.3 % of the study area in 2007 (Table 2.6). During the period 1956-2007, 19.5 Tg ha^{-1} of vegetation C was stored in forests in Andalusia. Among the agricultural classes, permanent crops are important contributors to vegetation C sinks in Andalusia with olive groves sequestering 5.23 Tg and fruit trees and berry plantations 3.00 Tg of vegetation C stock.

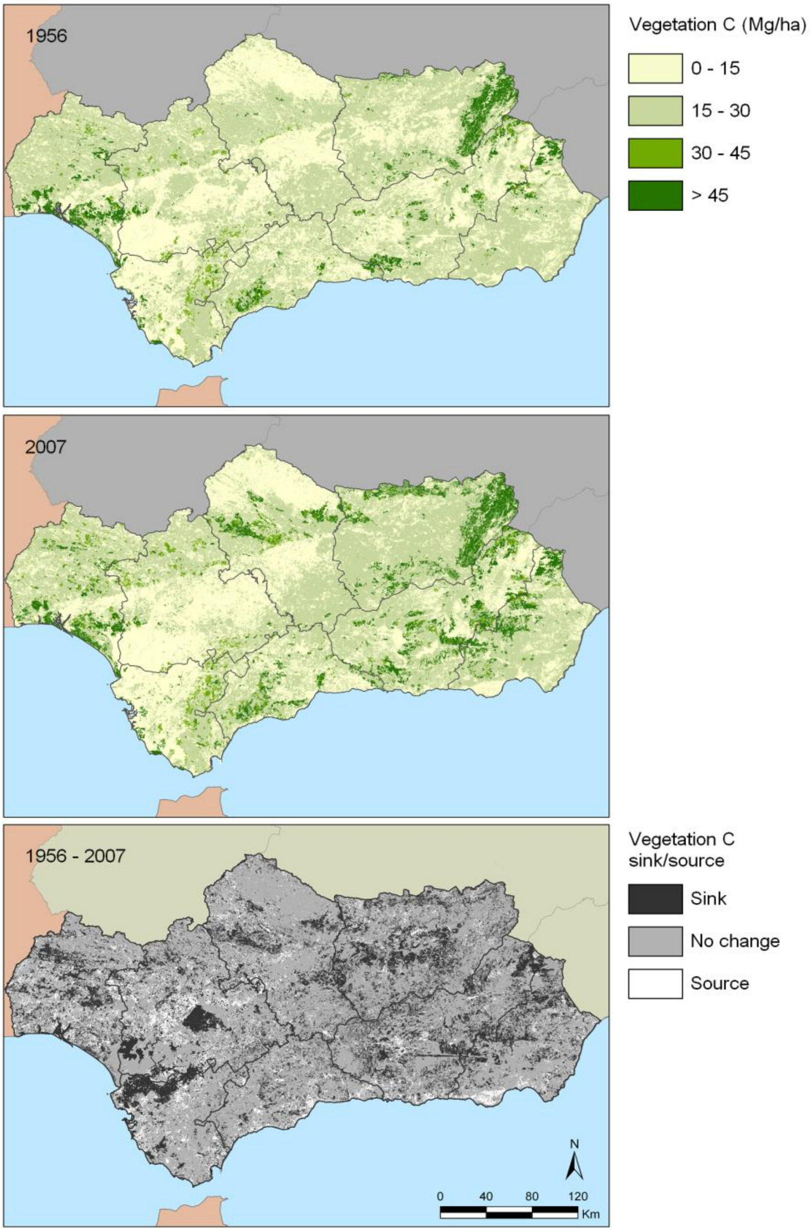


Figure 2. Vegetation carbon stocks in Andalusia in 1956, 2007 and vegetation carbon balance between 1956 and 2007.

Table 2.6.Vegetation carbon stocks in Mg (above and belowground biomass) in Andalusia in the period 1956-2007 at CLC Level 3 of nomenclature.

Class	Nomenclature	Area (ha)				C density	C vegetation stock				C vegetation balance
		1956		2007			1956		2007		
		ha	%	ha	%	Mg·ha^{-1}	Mg	%	Mg	%	Mg
111	Continuous Urban Fabric	27674.34	0.32	68758.96	0.78	0.00	0.00	0.00	0.0	0.00	0.0
112	Discontinuous Urban Fabric	7484.40	0.09	63197.51	0.72	3.23	24174.6	0.02	204128.0	0.13	179953.3
121	Industrial or commercial units	6155.24	0.07	34370.98	0.39	0.00	0.0	0.00	0.0	0.00	0.0
122	Road and rail networks and associated land	2429.81	0.03	20083.27	0.23	0.00	0.0	0.00	0.0	0.00	0.0
123	Port areas	368.45	0.00	1557.84	0.02	0.00	0.0	0.00	0.0	0.00	0.0
124	Airports	380.07	0.00	1395.52	0.02	0.50	190.0	0.00	697.8	0.00	507.7
131	Mineral extraction sites	3994.38	0.05	22461.60	0.26	0.00	0.0	0.00	0.0	0.00	0.0
132	Dump sites	90.59	0.00	3504.82	0.04	0.00	0.0	0.00	0.0	0.00	0.0
133	Construction sites	2047.49	0.02	38237.12	0.44	0.00	0.0	0.00	0.0	0.00	0.0
141	Green urban area	475.12	0.01	1339.41	0.02	6.46	3069.3	0.00	8652.6	0.01	5583.4
142	Sport and leisure facilities	171.72	0.00	8615.52	0.10	6.46	1109.3	0.00	55656.3	0.04	54547.0
211	Non-irrigated arable land	1877590.15	21.43	1077774.27	12.30	5.00	9387950.8	6.76	5388871.4	3.45	-3999079.4
212	Permanently irrigated land	195046.82	2.23	417788.11	4.77	5.00	975234.1	0.70	2088940.6	1.34	1113706.5
213	Rice fields	6885.21	0.08	43189.65	0.49	5.00	34426.1	0.02	215948.2	0.14	181522.2
221	Vineyards	28285.74	0.32	27678.51	0.32	21.00	594000.6	0.43	581248.7	0.37	-12751.8
222	Fruit trees and berry plantations	88086.65	1.01	230715.47	2.63	21.00	1849819.7	1.33	4845025.0	3.10	2995205.3
223	Olive groves	1216027.20	13.88	1464975.85	16.72	21.00	25536571.3	18.39	30764492.8	19.71	5227921.5
241	Annual crops associated with permanent crops	89345.87	1.02	76210.51	0.87	13.00	1161496.4	0.84	990736.6	0.63	-170759.8
242	Complex cultivation patterns	120571.66	1.38	323095.45	3.69	11.52	1388985.5	1.00	3722059.6	2.38	2333074.0
243	Land principally occupied by agriculture with nat.veg.	269845.49	3.08	204500.90	2.33	11.37	3068143.3	2.21	2325175.2	1.49	-742968.1
244	Agro-forestry areas	570190.98	6.51	538275.07	6.14	8.22	4686969.8	3.38	4424621.1	2.83	-262348.7
311	Broad-leaved forests	875500.19	9.99	918347.18	10.48	28.24	24724125.3	17.81	25934124.3	16.62	1209999.0
312	Coniferous forests	277999.00	3.17	541349.21	6.18	59.48	16535380.5	11.91	32199450.8	20.63	15664070.3
313	Mixed forests	83820.06	0.96	147541.36	1.68	40.80	3419858.3	2.46	6019687.6	3.86	2599829.3
321	Natural grasslands	331889.52	3.79	301141.77	3.44	3.04	1008944.1	0.73	915471.0	0.59	-93473.2
323	Sclerophyllous vegetation	1825926.91	20.84	1274476.43	14.55	17.74	32391943.3	23.33	22609211.8	14.49	-9782731.5
324	Transitional woodland-scrub	664419.98	7.58	711961.82	8.13	17.74	11786810.5	8.49	12630202.6	8.09	843392.1
331	Beaches. dunes. sands	9485.78	0.11	6273.87	0.07	1.50	14228.7	0.01	9410.8	0.01	-4817.9
332	Bare rocks	14904.03	0.17	30667.27	0.35	0.00	0.0	0.00	0.0	0.00	0.0
333	Sparsely vegetated areas	2808.75	0.03	3686.96	0.04	1.52	4269.3	0.00	5604.2	0.00	1334.9
334	Burnt areas	22.11	0.00	18771.38	0.21	0.00	0.0	0.00	0.0	0.00	0.0
421	Salt marshes	112055.67	1.28	55677.36	0.64	2.00	224111.3	0.16	111354.7	0.07	-112756.6
422	Salines	7565.81	0.09	14432.64	0.16	2.00	15131.6	0.01	28865.3	0.02	13733.7
511	Water courses	17080.84	0.19	18577.83	0.21	0.00	0.0	0.00	0.0	0.00	0.0
512	Water bodies	15152.38	0.17	47849.26	0.55	0.00	0.0	0.00	0.0	0.00	0.0
521	Coastal lagoons	183.56	0.00	307.95	0.00	0.00	0.0	0.00	0.0	0.00	0.0
522	Estuaries	324.44	0.00	1115.81	0.01	0.00	0.0	0.00	0.0	0.00	0.0
523	Sea and ocean	2295.95	0.03	443.98	0.00	0.00	0.0	0.00	0.0	0.00	0.0
	No data	5766.02	0.07	1	0.78						
	TOTAL	8.760.348.411	100.00	8760348.41	100.00		138836943.7	100.00	156079636.9	100.00	17242693.2

2.4. Discussion

2.4.1 Concerns about the used methodology

Although several studies have been carried out in Europe for different periods (see Nabuurs et al., 2003), very few studies have been done concerning the assessment and comprehensive analysis of LCCs and vegetation C dynamics in Spain. Some studies in Andalusia have addressed different methodologies, as “gain-loss” (Oliet Palá et al., 2007) and others (Pardos, 2010). The information generated in this research will contribute to better regional C inventories and will assist in establishing the basis for future studies on C emissions, baselines and mitigation scenarios associated with the land-use change processes.

After the Framework Convention on Climate Change at the Earth Summit in Rio de Janeiro (1992), different policies within local (e.g.: Andalusian Plan for Climate Action – Mitigation Measures (Carbon Sinks) and Andalusian Strategies for Climate Change), regional and global frameworks after the Kyoto (1997) and Buenos Aires (1998) summits are favouring actions to mitigate and adapt to climate change. Anyhow, further research is needed to help policy- makers to develop and justify climate change mitigation and land management policies. Furthermore, more evidence is required to exhibit the importance of ecosystems regarding their function and the services they provide to society together with the consequent benefits to the global economy. Over the past 50 years, human pressure over natural systems has been highly intense and the different ecosystems have changed in a greater extent than in any other equivalent period of time. At a global scale, this change is mainly due to growing demands for food, water, timber, fiber and fuel (Fitter et al., 2010). Because of the relevance of carbon stocks, knowledge about the mechanisms that underlie carbon sequestration and storage processes is especially important, in order to study the contribution of ecosystems and land use changes to climate regulation (Fitter et al., 2010). This study will also help the implementation of international initiatives that seeks to address the needs of decision-makers and the public in general for scientific information on the environment.

In agreement with Cantarello et al. (2010), we have considered that the only changes in vegetation carbon stocks are the result of LULCCs, while vegetation C stocks from areas where land use types remained stable between 1956 and 2007 are not being increased or decreased over time. Consequently, any map unit where land use has not changed is assumed to have zero carbon sequestration over time. Appreciable changes can occur in these stable areas because of tillage, logging, diseases or simply the age of plants (see, for example: USDA, 1998, Mol Dijkstra, 2009). More research is necessary in the assessment of possible changes in vegetation carbon stock in areas where land use is stable during a period of time in order to improve models.

Previous studies conducted in Mediterranean areas have provided estimates of C stocks in vegetation based on field measurements and/or remote sensing procedures. Thus, Garcia et al. (2010) used Lidar (Light Detection and Ranging) in a Mediterranean forest of central Spain for biomass C assessment. These techniques are expensive and difficult to apply at large scale and therefore measuring changes in C vegetation stocks is commonly done by estimating changes in C density and land use area based on inventory-type empirical approaches or net changes in each C pool. According to that method, Padilla et al. (2010) assessed land-use changes and associated C sequestration during the 20th century in rural areas of SE Spain. They established land use changes based upon local historical cadastres and the Spanish National Forest Survey and derived net ecosystem exchange and net primary productivity rates from literature. Changes in a C pool can be estimated using two approaches: a) C “gain- loss” (C accumulation is calculated from gain minus loss), and b) C “stock-difference” (difference between C stocks estimated at two different dates), which has been suggested for greater accuracy (Houghton et al., 2001; IPCC, 2007). For this work, vegetation carbon stocks were estimated following the “stock-difference” which considers all processes taking place in a given pool. We have followed a global approach based on the analysis of land cover changes during a 51-year period and the quantification of vegetation C stocks by using the Land Use and Land Cover Map of Andalusia (LULCMA) for years 1956 and 2007 and C density values from literature. These first estimates of vegetation C stocks depend to a considerable extent on the quality of land cover mapping and accuracy of C densities. Our approach does not intend to provide with accurate absolute values but it is meaningful in relative terms allowing comparing C vegetation stocks for different land cover classes and C sequestration trends associated to land-use changes.

The LULCMA for years 1956 and 2007 at scale 1:25.000 comprised a more detailed database than CLC data (scale 1:100000). Nevertheless, it was essential to reclassify into the European CORINE nomenclature since land inventories of C stores and fluxes should be comparable between different European CLC participants so that agreed reductions can be targeted. The used methodology is in agreement with Cruickshank et al. (2000) who used CLC and C density data derived for each land cover type to make an initial inventory of C stored in the vegetation of Ireland in 1990. Moreover, Tomlinson (2005) following the same method obtained measurements of C stocks in Ireland for 1990 and 2000.

2.4.2 Concerns about the quality and use of LULCMA maps

The accuracy and reliability of estimates of vegetation carbon stocks in the study area relies on the quality of the CLC mapping process. The methodology used for land cover mapping in the study area has been published including a detailed protocol for quality control and validation of data (Moreira, 2007). Since availability and type of data is largely different for both dates, validation of land use categories required different processes. Validation of 2007 land uses was achieved by systematic revision of a grid of points (spatially distributed every 5 km vertically and horizontally). In contrast, validation of land uses in 1956 required support of complementary maps and historical records. In spite of these controls, additional reviews of data were carried out by the authors in certain areas. Some limitations have been assumed when using CORINE classes. For example, CORINE has no specific class for shrubs, although shrubs are included in other classes (e.g.: 323, 324 or 333); more accuracy should be necessary in future research.

2.4.3 Land cover changes and vegetation carbon stocks

Assessing land-use change is useful for understanding the consequences of landuse dynamics under complex socio-economic and biophysical conditions. Since land use types differ in the amount of carbon stored in soil and vegetation (Arrouays et al., 2001; Bellamy et al., 2005; Lettens et al., 2005; Rodriguez-Murillo, 2001) and in the potential rate of carbon stock change, LUCs have significant effects on atmospheric concentration of greenhouse gases and carbon stocks in soil and vegetation (Feddema et al., 2005). The studied area has undergone intense changes in the past decades according to this research, with important consequences for vegetation C sequestration. According to this study, current land use patterns have led to a C sequestration of 17.24 Tg between 1956 and 2007, approximately at a rate of 0.34 Tg yr^{-1}. Total vegetation C stocks estimated were 156.08 Tg in 2007. Previous studies have reported 113.82 Tg in Great Britain (Milne and Brown, 1997), with 10.77 and 97.97 Tg for agricultural and woodlands, respectively; 24.7 and 22.7 Tg in Ireland for 1990 and 2000 (Tomlinson, 2005). The calculated C sequestration rate in forest areas in this research is 0.23 Mg ha^{-1} yr^{-1}. This value is minor than reported carbon sequestration rates calculated for forest biomass in Europe by several authors: 0.37 – 0.52 (Kauppi et al., 1992); 0.46 (Goodale et al., 2002), 0.30 (Ciais et al.,2008) and 0.30 Mg C ha^{-1} yr^{-1} (Kauppi et al., 2010). In contrast, lower carbon sequestration rates have been reported for forests in northern Europe, as 0.15 - 0.17 Mg C ha^{-1} yr^{-1} in Finland between 1922 and 2004 (Liski et al., 2006).

The most substantial land use change between 1956 and 2007 has been “intensification of agriculture”. Mediterranean agriculture in the twentieth century has been distinguished by a general tendency towards increased intensification. These intensive production practices have spread to a great extent and have been largely strengthened by the European Commission Policies such as the Common Agricultural Policy (CAP) along with population growth (Caraveli, 2000; Wainwright and Thornes, 2004). This is in agreement with Feranec et al. (2010), who have shown that the most extensive LC change areas induced by “intensification of agriculture” in Europe during the last years have been observed in Spain. Our results show that this LCF in the study area has been characterized by an increase in the area of olive groves, irrigated crops and greenhouses.

“Intensification of agriculture” has resulted in a total sequestration of 8.14 Tg of vegetation C between 1956 and 2007, which is in agreement with results from several authors (e.g., Houghton and Hackler, 1999; Bolliger et al., 2008). The major contributors are olive orchards and fruit trees and berry plantations with respectively 5.23 and 3.00 Tg of sequestered C. The agricultural sector contributes as a substantial source of CO_2 but can play an important role as a C sink increasing C sequestration through trees, plants and crops which absorb CO_2 from the atmosphere through photosynthesis and store it as C in the biomass. In Mediterranean areas, olive groves and other permanent crops such as fruit orchards spread over a large area and therefore may be significant for C sequestration (Sofo et al., 2005). However, the process of intensification has several environmental implications in the region since it is associated to the use of environmentally polluting inputs such as pesticides and to high fertilizer consumption (Caraveli, 2000). “Extensification of agriculture” affected a considerable area in the studied period, which means that a large area associated to arable land or permanent crops has been transformed to pastures and other lower intensity uses of agriculture. This change is often the consequence of abandonment of several mountainous regions leading to a substantial decline in arable land (Caraveli, 2000). Land abandonment is linked to soil erosion, reduction of water stocks and biodiversity loss but may have a positive approach raising opportunities to “afforestation”.

The process of “afforestation” (conversion of agricultural land and semi-natural areas to forests) was a considerable change in the period 1956-2007. “Afforestation” is associated with the transformation of land (usually open land) into forest (Feranec et al., 2010). Several policies at different regional and national levels have promoted afforestation including the farmland afforestation program within the EU's PAC and the Forestry Plan of Andalusia in 1989. Afforestation of land has been in many cases an alternative to land abandonment, additionally contributing to the restoration of degraded forest landscapes. Moreover, afforestation is associated to other positive effects such as improvement of habitat suitability for wildlife and soil and water quality (Montiel-Molina, 2006). In the study area, carbon sink due to afforestation accounts for 64.2 % of total carbon sink between 1956 and 2007. The total amount of vegetation carbon stock in re-afforested land (17.73 Tg) is comparable to total vegetation carbon sink in the studied area in 2007 (17.24 Tg). All CLC classes conforming forest types (broad-leaved, coniferous and mixed forests) have increased in the region according to the results of this study. Coniferous forests have doubled the area during the last 51 years. These species have been the most commonly used in the Mediterranean area during the 20th century in afforestation projects and especially *P. halepensis* and *P. pinaster* considered species tolerant of many climates and soils (Maestre et al., 2003; Ruiz-Navarro et al., 2009). These species are the most frequent coniferous in the study area together with *P. nigra*, *P. sylvestris* and *P. pinea* widely used in afforestation programmes. Nevertheless it has been subjected to criticism since some studies carried out in the western Mediterranean basin have demonstrated that planted pine woodlands have a negative impact on diversity of the local flora and fauna (Andres and Ojeda, 2002). There were significant increases in vegetation C stocks after ”afforestation” in the region, with coniferous forest as major contributors to aboveground C sequestration. During the 51-year studied period, coniferous forests were the main sinks of C in alive vegetation, sequestering 15.66 Tg C in aboveground biomass. Mixed forest composed by broad-leaved and coniferous formations show a high C vegetation density. However, this land cover class only takes up 1.68% of total area in 2007, representing 3.86% of the total C stock with a C sequestration of 2.60 Tg between 1956 and 2007. Despite the slight increase of areas covered by broad leaved forest, they are major contributors to C stocks conforming 16.62 % of the total vegetation stock in 2007 and a sequestration of 1.21 Tg C in aboveground biomass. “Deforestation” is not a major change, although an appreciable area has been affected by these processes. Changes of forest into transitional woodland-scrub and other semi-natural areas is the result of the anthropogenic impacts in forests (Feranec et al., 2010), consisting mainly of the conversion of forest cover to scrub and/or herbaceous vegetation associations and to heterogeneous agricultural areas. Carbon gains through “intensification of agriculture” and “afforestation” are partly offset by C losses following “extensification of agriculture” (cropland abandonment) and “deforestation” which have produced C losses of 1.58 Tg and 5.60 Tg respectively.

“Urbanization” reflects the conversion of agricultural and forest land into artificial surfaces. Although the total percentage is low in comparison with the total land change area it is remarkable how urban growth and construction of new industries and infrastructures have increased the surface of this land cover to a great extent. Despite its low percentage of land cover change, “urbanization” affected vegetation C stocks by reducing 2.57 Tg in the 51-year period. “Construction of water bodies” has not affected significantly the area, consisting of 0.5% of the total surface, but it contributed to vegetation C loss with 0.63 Tg.

2.5. Conclusions

In this work we use a comprehensive and global approach for land cover change and vegetation C dynamics based on accurate spatial datasets adapted to the European CORINE nomenclature and following the IPCC Guidelines. The proposed methodology is easily applicable to other countries, and our research provides with first estimates of C vegetation stocks and allows analysing C sequestration trends associated to land-use changes. Land cover dynamics in the region of Andalusia in Southern Spain between 1956 and 2007 have been significant, affecting 33.7% of the area. Land cover changes have lead to a C sequestration of 17.24 Tg (approx. 0.34 Tg C $ha\text{-}^{1}$ yr^{-1}) in the vegetation, mainly due to “afforestation” and “intensification of agriculture” resulting in a total vegetation C stock of 156.08 Tg in 2007 with coniferous forests and olive groves as major contributors. This study demonstrates the importance of land cover change for C sequestration in vegetation of Mediterranean areas like Southern Spain and indicates possible directions for land cover policy in order to increase sequestration of atmospheric CO_2. Future efforts should consider improvement of vegetation C densities assimilated to the study area. Although increases in vegetation C stocks may be achieved in a short period of time and are politically interesting there is a need to extend the work on soil C stocks considering soils contain about twice the amount of C in the atmosphere and three times the amount in vegetation (IPCC, 2000, 2007). We are conducting further work to determine the influence of land cover change on soil C stocks and to evaluate soil capacity for C sequestration.

CHAPTER 3

IMPACT OF LAND USE AND LAND COVER CHANGES ON ORGANIC CARBON STOCKS IN MEDITERRANEAN SOILS (1956 – 2007)

3.1 Introduction

The effects of land use and land cover change (LULCC) have become a key issue for the scientific community concerned with global environmental change (Lambin and Geist, 2006). During the past 50 years, ecosystems have been altered more rapidly and extensively than at any other time in history, especially in the Mediterranean region (Serra et al., 2008; Steffen et al., 2011), where soils have been cultivated for millennia. Human-induced LULCCs have contributed to soil degradation and soil loss, leading to a decrease of soil C storage worldwide (Eaton et al., 2008), more intensely during the last decades in the Mediterranean areas (Cerdà et al., 2010). In recent years, LULCCs, especially deforestation and agricultural intensification, have largely affected the global warming process through emissions of CO_2 (Houghton and Hackler 1999; Lambin et al., 2001; Ostle et al., 2009; Schulp et al, 2008). After fuel consumption, LULCC is considered the second major cause of CO_2 emissions (IPPC, 2007; Watson et al., 2000).

Soil organic C (SOC) is the largest C stock in most terrestrial ecosystems and it plays an important role in the C cycle (Lal, 2004). It has been estimated that SOC stocks in the world account for 1462-1545 Pg to a depth of 1 m, and 684-724 Pg in the upper 30 cm (approximately 50%), the soil layer most prone to change upon land management or climate change (Batjes, 1996). Although most of the studies assess SOC dynamics only in the topsoil, a considerable amount of SOC can be stored in deeper layers. In addition, this form of C has proven to be more stable (Jobbagy and Jackson, 2000). Soil organic C stocks are determined by the balance of net C inputs into the soil (organic matter) and net soil C losses (mainly as C dioxide), and they can be intensely modified by LULCC (Guo and Gifford, 2002). Using data from the literature, Guo and Gifford (2002) showed that different LULCCs induced soil C losses or gains, but soil C declined on average by 9% after LULCC. They also suggested that soil C losses after LULCC are difficult to revert since long periods of time are needed to recover the original level of soil C stock. Some authors have suggested that LULCC is the main factor determining SOC stocks at scales of decades to centuries (Scott et al., 2002).

Currently, the contribution of soils as C sinks to global warming reduction is a matter of debate (Kutilek, 2011). However, there is a growing interest in quantifying and understanding soil C stock changes over time, as a consequence of the rise in atmospheric CO2 and the role of soils in C sequestration (Lantz et al., 2001; Smith, 2008; Eaton et al., 2008; Wang et al., 2011). Carbon sequestration is defined as any increase in the C content of soils after a change in land management (Powlson et al., 2011) and is one of the most important ecosystem services because of its role in climate regulation (IPCC, 2007). Worldwide, the potential capacity for SOC sequestration has been estimated between 0.4

and 1.2 Gt year^{-1}. The balance between inputs of organic matter and C loss by natural conversion to CO_2 and CH_4, erosion or hydrological C export, determines whether the soil is sequestering C (Lal, 2004). Soil organic C tends to decrease when transforming grasslands, forest or other native ecosystems to croplands, and to increase when restoring native vegetation on former croplands, or by restoring organic soils to their native condition (Guo and Gifford, 2002). Nevertheless, although soils converted from natural vegetation to arable land decline in SOC content, after a period of time a new equilibrium level is reached. Dawson and Smith (2007) reported an increase of more than 50% in SOC stocks after the conversion from arable to forest land, whereas other authors have found either a decrease or no significant change after afforestation (Chen et al., 2004; Farley et al., 2004).

Several studies have estimated the impact of LULCC change on SOC stocks by using a paired site methodology (Novara et al., 2012; Wellock et al.2011). In the paired site approach, sites with a similar type of soil and different land uses (LUs) are selected. Soil types differ in their properties and their capacity for C storage (Eswaran et al., 2003; Gamboa and Galicia, 2011), thus LULCC has different impact on different soils. Other methods use a combination of soil maps and land cover data as for example in Bradley et al. (2005) and Eaton et al. (2008). Nevertheless, a high density of soil sampling points and a high resolution of spatial databases are desired in this case to obtain reliable results (Martin et al., 2011). Although Mediterranean areas show high potential for C sequestration due to their low soil organic C content (Romanya et al., 2007), few studies have been carried out in the study area regarding LULCC impacts on SOC stocks and SOC sequestration (Ruiz Sinoga et al., 2011). Soil organic C decline is of particular concern in this region with high temperatures, drought periods and heavy rainfall events (Romanya et al., 2007)

The main goal of this research is to assess the impact of land use changes on SOC stocks at regional scale and the spatial variability of soil organic C stocks between 1956 and 2007. The specific objectives of this study are [1] to quantify SOC stocks in 1956 and 2007 in Andalusia (southern Spain) at different depths in the soil profile, [2] to analyse the influence of LULCCs between 1956 and 2007 on SOC stocks of representative Mediterranean soil groups, [3] to assess the rates of change in SOC stocks for different LULCCs.

3.2 Materials and methods

3.2.1 Origin of data and treatment

Soil data

Data from 1357 geo-referenced soil profiles reported and described by Jordán and Zavala, (2009) and the SEISnet soil database[1] have been used. These soil profiles are distributed throughout the study area. The soil databases contain descriptive and analytical data, including site characteristics, horizon description and chemical and physical analysis. Selection of soil profiles was performed considering homogeneous sampling and analysis methods. Variables used in this study were soil depth (cm), organic C content (g 100 g^{-1} soil), bulk density (g cm^{-3}) and coarse fragments (mineral particles >2 mm in diameter). Organic C was determined by dichromate oxidation using the Walkley-Black method (Walkley and Black, 1934). Bulk density was measured by the core method (Blake and Hartge, 1986).

Soil profiles were re-coded and imported to the SDBm Plus Multilingual Soil Profile Database (De la Rosa et al., 2003; De la Rosa et al., 2002) to normalize information. The SDBM Plus is a geo-referenced soil attribute database that contains a large number of descriptive and analytical data fields. Since soil profiles showed a range of depths, data were homogenised and re-sampled for 0-25, 25-50 and 50-75 cm. The SDBm Plus database includes a "control section" function, to determine the thickness of the layer to be analysed within the soil profile. This function allows calculating the weighted average value for each variable in standard control sections.

Land use and land cover data

Land use classification and land cover data for the selected soil profiles were extracted from the Land Use and Land Cover Map of Andalusia (LULCMA) for 1956 and 2007 at scale 1:25,000 and minimum map unit 0.5 ha (Moreira, 2007). The established CLC nomenclature comprises 44 land cover classes, grouped in 5 main classes at level 1 Level 2 (15 classes) corresponds to physical and physiognomic entities at scales 1:500,000 and 1:1,000,000 ("Urban zones", "Forests", "Lakes", etc). Finally, level 3 is composed of 44 classes for use at scale 1:100,000 and higher (Heymann et al., 1994). The CLC classification is explained in more detail in Chapter 2. Land cover classes of LULCMA were reclassified into CLC nomenclature in order to be used for other CORINE programme member countries and thus, obtain easily comparable results (Muñoz-Rojas et al., 2011).

---

[1] http://www.evenor-tech.com/banco/seisnet/seisnet.htm

3.2.2 Calculation of soil organic C stocks

For every soil layer of the 1357 soil profiles (0-25, 25-50 and 50-75 cm), soil organic C content (SOCC) was estimated as follows:

$$\text{SOCC} = \text{SOC} \times \text{BD} \times \text{D} \times (1\text{-G}) \qquad (1)$$

where SOCC is soil organic C content (Mg ha^{-1}), SOC is soil organic C percentage (g 100^{-1} g^{-1}), BD is bulk density (g cm^{-3}), D is the thickness of the studied layer (cm) and G is the proportion in volume of coarse fragments. Soil profiles were classified according to original soil profile descriptions, into 8 soil reference groups (IUSS Working Group WRB, 2006): Arenosols, Calcisols, Cambisols, Fluvisols, Leptosols, Luvisols, Regosols and Vertisols; and 7 LU types following CLC nomenclature at level 2: “arable land”, “permanent crops”, “heterogeneous agricultural areas”, “forest”, “scrub and/or vegetation associations”, “open spaces with little or no vegetation” and “maritime wetlands”. Subsequently, soil profiles were divided in groups with the same land use class and soil group (landscape units), and mean values of SOCC (Mg ha^{-1}) were calculated for each of these units.

To determine SOC stocks, the study area was divided into LULC and soil association units (landscape units), using a topological intersection of the Soil Map of Andalusia (CSIC-IARA, 1989) at scale 1:400,000 and both the LULCMA for 1956 and 2007. The overlay of both maps produced a new spatial dataset composed of 858,110 new polygons in 1956 and 858,446 in 2007, defined by 1 soil group (dominant unit) and one aggregated land cover type. Mean values of SOCC (Mg ha^{-1}) of each landscape unit were assigned to all the new polygons in 1956 and 2007 and SOC stocks were determined by multiplying SOCC mean values by the area occupied by the landscape unit in the overlay maps. Data analysis was performed using SPSS (SPSS, 2009) and ArcGIS (ESRI, 2006) software packs.

3.2.3 Impact of land use change on soil organic C stocks

To identify the effects of LULCC between 1956 and 2007 on the SOC concentrations of the soil groups at different depths, soil profiles were classified according to different land use changes, following CLC nomenclature at level 2 (Table 3.1). Each soil profile was also classified at different scale according to major Land Cover Flows (LCFs) between 1956 and 2007. These LCFs, defined on the second level of CLC legend, consist of LC changes grouped and classified according to major LU processes (Feranec et al., 2010; Muñoz-Rojas et al., 2011). In this study we considered 4 LCFs: 1) “Intensification of agriculture”, 2)”Extensification of agriculture”, 3)”Afforestation” and 4)”Deforestation”. For each of the LULCC and LCF groups, statistical parameters (mean value and standard deviation) and rates of SOC changes were determined for the different soil groups at different soil depths. Data analyses were performed using SPSS (SPSS, 2009) and Statistica (StatSoft, 2001).

Table 3.1. Soil organic carbon content changes (%) of different soil groups following land cover flows (LCFs) and land use and land cover changes (LULCCs)

LCFs / LULCCs	**Arenosols**	**Calcisols**	**Cambisols**	**Fluvisols**	**Leptosols**	**Luvisols**	**Regosols**	**Vertisols**
Intensification of agriculture								
Arable land to permanent crops	-63%	-24%	18%		-47%	14%	9%	-11%
Heterogeneous agricultural to arable land	-3%	-17%	101%				20%	
Heterogeneous agricultural to permanent crops			217%		46%	40%	-57%	
Scrub to arable land	-72%	-26%	19%	-15%	-35%	-67%	-7%	-4%
Scrub to heterogeneous agricultural	-89%		34%	21%	-48%	-57%	-27%	
Scrub to permanent crops	-54%		193%		-52%	1%	-28%	
Extensification of agriculture								
Arable land to heterogeneous agricultural	43%	0%	12%	26%	-32%	97%	-12%	-4%
Permanent crops to arable land	27%	-5%	17%	364%	2%	-29%	-5%	11%
Permanent crops to Heterogeneous agricultural		10%					-37%	
Afforestation								
Arable land to forest			69%	-33%			17%	
Arable to scrub		16%	-6%	-11%	-27%	23%	36%	-77%
Heterogeneous agricultural to forest	-11%	-40%	-40%	-56%	-32%		35%	
Heterogeneous agricultural areas to scrub		-58%	130%		60%	66%	-75%	
Scrub to forest	-11%	46%	25%	-88%	1%	-11%	-28%	
Deforestation								
Forest to arable land				45%		23%	-51%	
Forest to heterogeneous agricultural	155%	33%	-90%		7%	-77%	-81%	
Forest to permanent crops		-66%	-84%		54%		-73%	
Forest to scrub	18%	14%	-55%		95%	-91%	-61%	
Scrub to open spaces					-66%		-94%	

3.3 Results

3.3.1 Changes in soil organic C stocks between 1956 and 2007

Spatial distribution of SOC stocks in 1956 and 2007, and SOC sequestration in Andalusia is shown in Fig 3.1. Estimated SOC stocks were 431.1 Tg in 1956 and 414.3 Tg in 2007 (data not shown in tables), which imply SOC loss of 16.8 Tg from 1956 to 2007. Changes in SOC stocks between 1956 and 2007 for each soil group and LULC class are shown in Table 3.2. Land use changes during this period implied C losses in all soil groups, with larger average decreases in Arenosols, Fluvisols and Calcisols. These soil groups showed a C loss of 8.1, 7.6 and 5.7 % respectively in the 51 years period. In absolute terms, Cambisols and Regosols have lost 5.4 and 4.6 Tg respectively between 1956 and 2007. Among land use types, the largest declines in SOC contents were observed in “maritime wetlands” with a loss of 42.2% and in “arable land” with a negative rate of 27%. Total SOC stocks of “arable land” and “scrub and/or herbaceous vegetation associations” have decreased 31.0 and 28.3 Tg respectively. On the contrary, “forests” contributed to sequestration of 8.62 Mg ha^{-1} (25.4%) and “open spaces with little or no vegetation” to 8.72 Mg ha^{-1} (86.1%). “Permanent crops” and “heterogeneous agricultural areas” accumulated 13.36 Mg ha^{-1} and 54.52 Mg ha^{-1} respectively.

3.3.2 Soil organic C contents and sequestration rates

Figures 3.2 y 3.3 summarize the variation of SOC contents for the studied LCFs between 1956 and 2007. Supplementary tables S3.1 and S3.2 show detailed changes of SOC contents for each LULCC and soil group at different depths in the soil profile (0-25, 25-50 and 50-75). Conversions among LULC classes show substantial impacts on SOC contents, with considerable differences among soil groups. In general, SOC contents are larger in the surface layer declining with depth. However, some changes among agricultural classes showed an increase of SOC stocks in lower layers (25-50 or 50-75), e.g. Arenosols and Regosols when “permanent crops” are transformed to “arable land”. Soil organic carbon sequestration rates for 0-75 depth are displayed in Table 3.1 (see also supplementary Table S3.3 for more information). Over the 51 years period, changes from “arable land” to “permanent crops” lead to a SOC decrease of 63% in Arenosols, 47% in Leptosols and 24% in Calcisols. However, the same conversion contributed to SOC accumulation in Cambisols (18%), Luvisols (14%) and Regosols (9%). Transformation from “heterogeneous agricultural areas” to “arable land” induced accumulation of SOC in Cambisols and Regosols (101% and 20%, respectively), and losses in Calcisols (17%). Small changes were observed in Arenosols with approximately a SOC decrease of 3%.

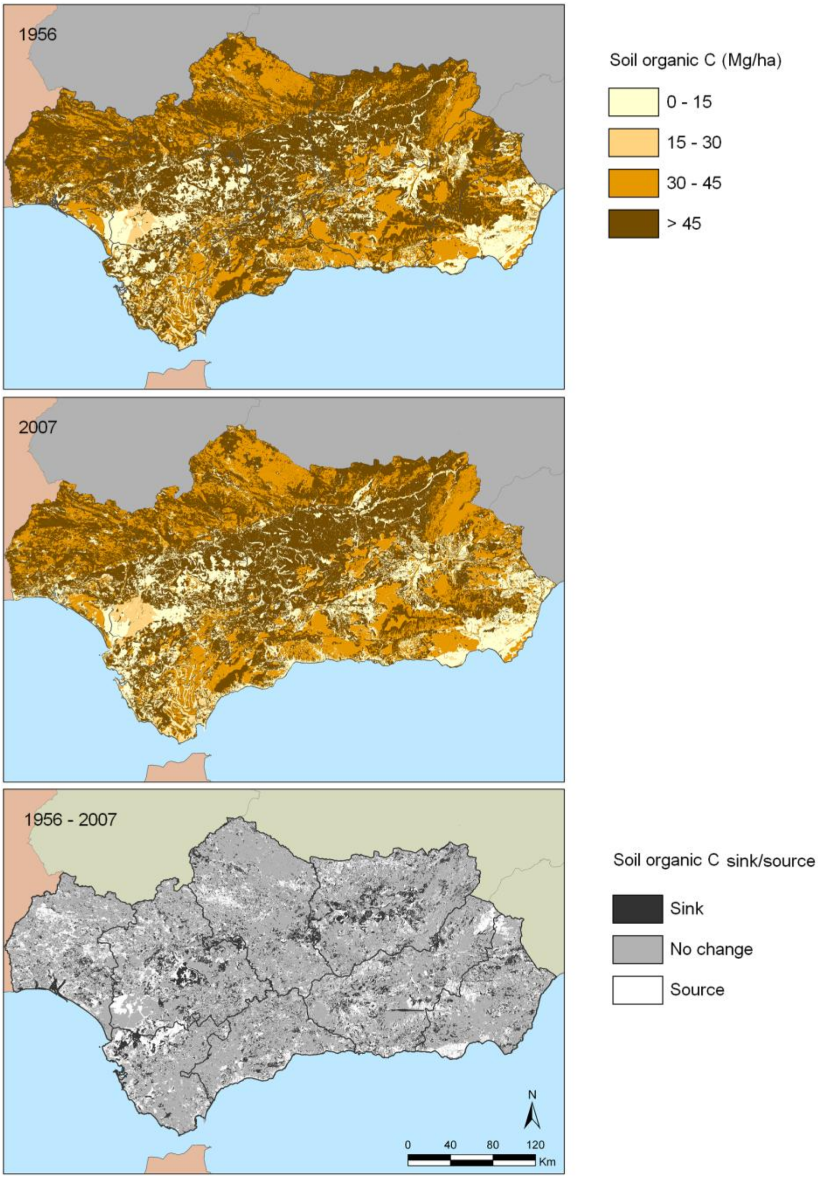


Figure 3.1. Soil organic carbon stocks in 1956, 2007 (Mg/ha) and soil organic carbon sink/ source areas.

As a consequence of land use changes from “scrub” to agricultural uses, i.e. “arable land”, “heterogeneous agricultural areas” and “permanent crops”, SOC stocks decreased in Arenosols, Calcisols, Leptosols, Luvisols and Regosols. In particular, Arenosols supported intense SOC losses when “scrub” was converted to “arable land” and “heterogeneous agricultural areas” (72 and 89% respectively). In Cambisols, transformation from “scrub” to agricultural uses increased SOC contents.

On the contrary, extensification of agriculture contributed to an overall increase of SOC stocks in most of soil groups. In Arenosols, Cambisols, Fluvisols and Vertisols, SOC stocks enlarged through LULCC “permanent crops” to “arable land”, with rates of SOC change up to 364% in Fluvisols. Yet, SOC stocks decreased in Calcisols, Regosols (5% in both soil types) and Luvisols (29%). In Leptosols and Regosols, minor changes were observed In the first 25 cm of Arenosols, SOC contents decreased from 39.2 to 28 Mg ha^{-1}, after the conversion from “arable land” to “heterogeneous agricultural areas” (supplementary Table S3.1). Nonetheless, in the total soil depth (0-75 cm) SOC increase approximately by 43%. After the same LU conversion, SOC from Luvisols enlarged by 97 % (Table 3.1).

Conversion from “heterogeneous agricultural” areas to “forest” contributed to increase SOC in Regosols (35%). In Calcisols, SOC stocks increased only in the first 25 cm from 38.2 ± 32.4 to 47.8 ± 55.7 Mg ha^{-1} (supplementary Table S3.1). However, this transformation lead to SOC contents decreases in Arenosols, Cambisols, Fluvisols and Leptosols (Table 3.1). Changes from “arable land” to “forest” increased SOC stocks in Regosols from 34.7 Mg ha^{-1} to 70.1 Mg ha^{-1} in the first 25 cm. In contrast, differences are less significant for the total depth of the soil profile (first 75 cm) with values of SOC stocks rising from 62.5 to 73.4 Mg ha^{-1} (supplementary Table S3.3) and a rate of change in SOC contents of 17% (Table 3.1). In Cambisols SOC stocks increased by 69%, mostly in the top layers (Figure 3). Likewise, conversion from “heterogeneous agricultural areas” to “forest” accumulated SOC in Regosols (35%), although SOC stocks decreased with this LULCC in Arenosols, Calcisols, Cambisols, Fluvisols and Leptosols, with SOC sequestration rates between 11 and 56%. Transformation from “scrub” to “forest” resulted in a SOC increased in Calcisols, Cambisols and Leptosols. Land use changes from “forest” to “arable land” caused a substantial decline of SOC contents in Regosols (51%), but positive rates were found in Fluvisols and Luvisols. Similarly, SOC stocks largely decreased after transformation of “forest” to “heterogeneous agricultural areas” in Regosols (-77%) as well as in Luvisols and Cambisols (negative rates of 77 and 90% respectively). Conversely, in Arenosols Calcisols and Leptosols soil C sequestration rates were positive and ranged from 7% to 155%. Conversion from “forest” to “permanent crops” caused considerable SOC losses in Calcisols (changing from 69.3 ± 35.3 to 23.9± 0.0 Mg ha^{-1}), Cambisols (61.9 ±

59.7 to 9.8 ± 0.0) and Regosols (60.7 ± 63.9 to 16.3 ± 0.0) (supplementary Table S3.3). Transformation from “scrub” to “open spaces” resulted in a large decline of SOC contents in Regosols and Leptosols (94 and 66%, respectively).

Table 3.2. Changes in soil organic contents (Mg ha^{-1}, %) and stocks (Tg) for different soil groups and land uses between 1956 and 2007.

Land use/ Soil group	Arable land	Permanent crops	Heterogeneous agricultural areas	Forest	Scrub and/or herbaceous vegetation associations	Open spaces with little or no vegetation	Maritime wetlands	Total
Arenosol								
Mg ha^{-1}	10.4	17.2	-15.4	-2.3	-10.6	4.2	0.0	-3.2
%	57.0	111.8	-23.6	-6.4	-19.6	33.2		-8.1
Tg	0.1	0.0	-0.0	-0.1	-0.2	0.0	0.0	-0.2
Calcisol								
Mg ha^{-1}	-1.8	34.23	3.1	30.0	-15.36	0.0	0.0	-4.1
%	-3	159.9	4.0	44.9	-18.8			-5.7
Tg	-0.1	0.4	0.1	0.1	-1.3	0.0	0.0	-0.7
Cambisol								
Mg ha^{-1}	-28.0	17.0	1.5	6.8	-15.2	0.0	0.0	-1.5
%	-37.0	39.6	4.5	25.6	-22.4			-3.2
Tg	-12.4	12.3	1.0	6.2	-12.5	0.0	0.0	-5.4
Fluvisol								
Mg ha^{-1}	-22.8	19.2	5.7	1.5	-7.3	0.0	-53.9	-4.5
%	-29.0	45.4	10.2	3.4	-15.9		-33.4	-7.6
Tg	-3.3	1.8	0.3	0.1	-0.5	0.0	-0.3	-1.9
Leptosol								
Mg ha^{-1}	-31.7	8.2	-7.0	12.8	-6.1	11.6	0.0	-0.3
%	-45.0	42.2	-15.6	45.2	-13.0	35.1		-0.9
Tg	-0.8	0.5	-0.3	2.6	-2.4	0.1	0.0	-0.3
Luvisol								
Mg ha^{-1}	-3.3	1.0	-9.4	3.3	-13.4	0.0	0.0	-2.8
%	-6.0	1.8	-15.6	5.8	-20.8			-4.9
Tg	-0.5	0.3	-0.8	0.4	-1.3	0.0	0.0	-2.0
Regosol								
Mg ha^{-1}	-34.3	10.7	0.6	16.8	-22.0	22.6	-10.2	-2.8
%	-35.0	26.8	1.4	43.2	-26.3	153.6	-34.9	-4.8
Tg	-7.0	4.1	0.1	7.5	-9.6	0.4	-0.0	-4.6
Vertisol								
Mg ha^{-1}	-25.9	22.1	59.6	-13.4	-4.5	0.0	0.0	-1.4
%	-27.0	60.4	397.4	-12.0	-13.9			-2.1
Tg	-9.4	3.6	5.8	-0.8	-0.3	0.0	0.0	-1.1
Total								
Mg ha^{-1}	-20.1	13.4	5.5	8.6	-14.2	8.7	-50.3	-2.0
%	-27.0	32.3	14.8	25.4	-21.7	86.1	-42.2	-3.9
Tg	-31.0	23.0	6.2	16.1	-28.3	0.5	-3.2	-16.8

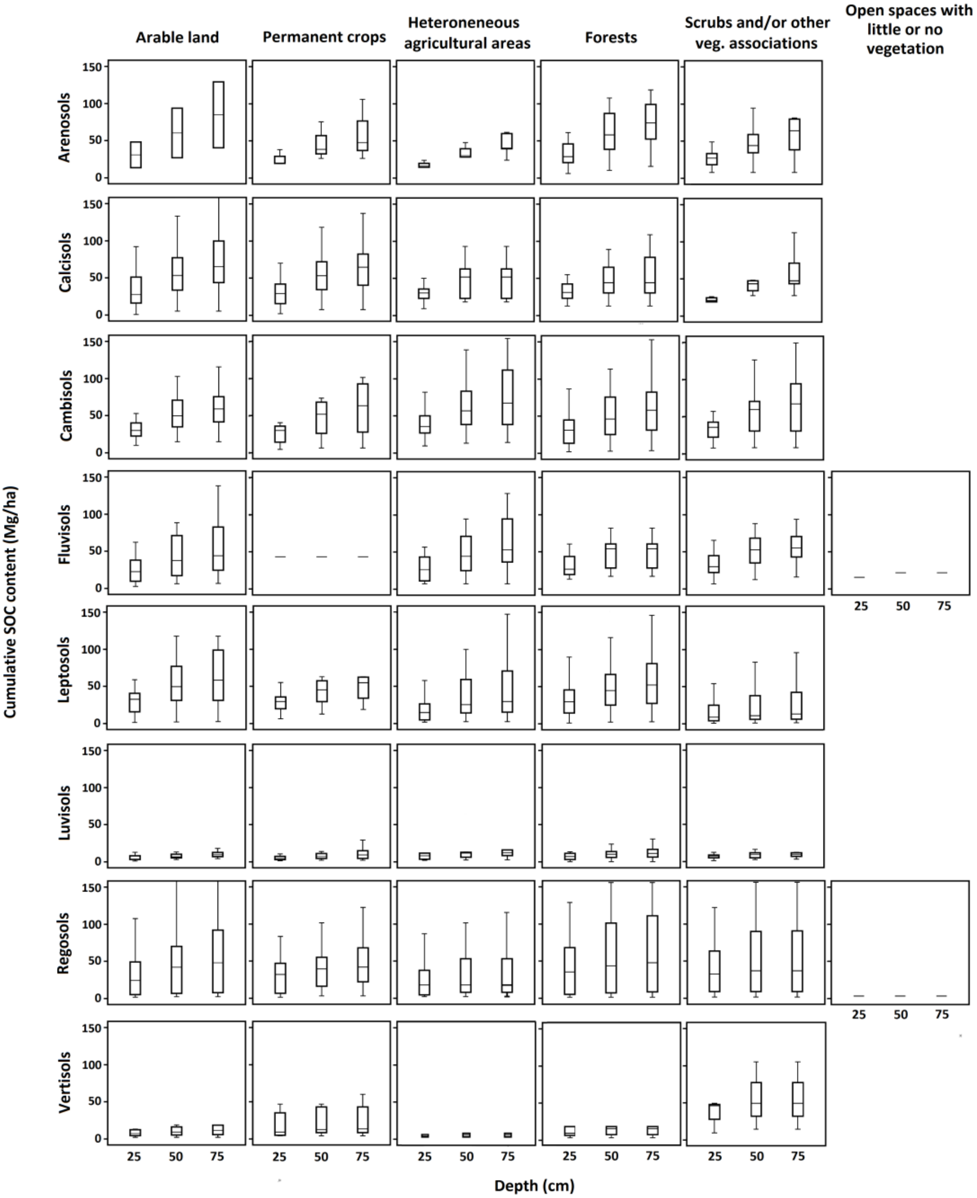


Figure 3.2. Cumulative soil organic C content (Mg ha^{-1}) from Arenosols, Calcisols, Cambisols and Fluvisols for land uses without change between 1956 and 2007 at different depths (0-25, 25-50 and 50-75 cm).

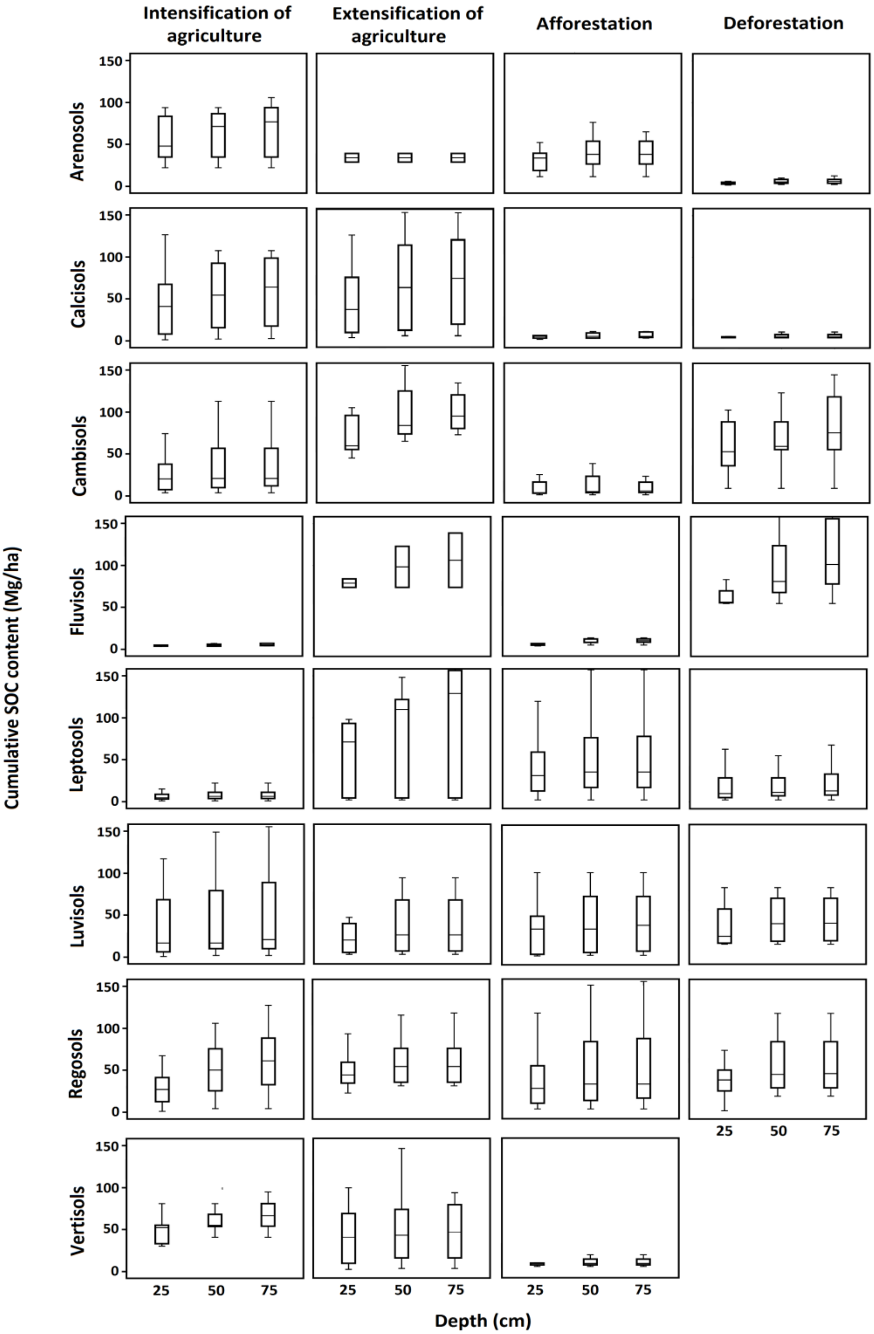


Figure 3.3. Cumulative soil organic C stock (Mg ha-1) from Arenosols, Calcisols, Cambisols and Fluvisols for each land cover flow (LCF) between 1956 and 2007 at different depths (0-25, 25-50 and 50-75 cm).

3.4 Discussion

3.4.1 Changes in soil organic C stocks

In the last years, southern Spain has gone through extensive LULCCs (Bermejo et al., 2011) with important consequences for SOC stocks and SOC sequestration. According to this research, LULCC changes between 1956 and 2007 have led to SOC loss of 16.8 Tg (approximately at a rate of -0.33 Tg year^{-1}). Previous studies estimated a C accumulation of 17.24 Tg and a rate of 0.34 Tg C year^{-1} in the vegetation of Andalusia during the same period (1956-2007) (Muñoz-Rojas et al., 2011). Increases in vegetation C stocks may be achieved in a short period of time, as compared to soil C, due to the slow rates of soil organic matter turnover. After a disturbance, soil organic accumulation following LULCC is more rapid during the first years, and it ceases as a new equilibrium value is reached. The period necessary for sink saturation (the new equilibrium) is variable. In temperate locations, such as Europe, some authors reported approximately a few decades (Arrouays et al., 2001) while others estimated around 100 years (Smith, 2004). However, the process is reversible, and SOC stocks will remain stable as long as LULC or management practices remain constant.

Our estimates are in agreement with results obtained by Van Wesemael et al (2004). In their studies, a decrease in SOC stock for Belgian croplands of -0.3 Mg C ha^{-1} yr^{-1} was reported from 1990 to 2000, similar to the SOC loss of -0.39 Mg C ha^{-1} yr^{-1}. Moreover, Bellamy et al (2005) used data from the National Soil Inventory of England and Wales to estimate SOC changes between 1978 and 2003, obtaining 0.31 Mg C ha^{-1} yr^{-1}, in consistence with our results.

3.4.2 Impact of land use change on SOC sequestration

European agricultural policies along with population growth have favoured intensive production uses, increasing agriculture productivity and therefore carbon contents in the overall aboveground biomass of the area (Muñoz-Rojas et al., 2011). Differently, processes involving intensification of agriculture in Southern Spain have exposed a negative effect on SOC stocks, in particular when “scrub” were converted to agricultural uses in Arenosols, Leptosols and Regosols. Among intensification processes, conversion from “arable land” to “permanent crops” slightly increased SOC stocks in fertile soils (Cambisols, Luvisols and Regosols). However, it implied minor SOC sequestration rates ranging from 9 to 18%. This might be explained by the limited effect that agricultural management in “permanent crops” has on SOC sequestration (Smith, 2004). In Arenosols, Calcisols and Vertisols, this land use conversion involved important losses of SOC with negative rates of 63%, 24% and 11% respectively. Novara et al (2012) obtained comparable values in their study of SOC dynamics after 30 years in a Mediterranean semiarid environment. In their research a 12.5% loss of SOC was estimated when vineyards were transformed into “arable land”.

Over 500,000 ha of Andalusia have supported land use changes associated to extensification of agriculture such as transformation of “arable land” or “permanent crops” to low intensive uses (Muñoz-Rojas et al., 2011). These changes showed different patterns of SOC sequestration depending on the soil type, but in general they implied an increase of SOC contents. In Cambisols, Fluvisols and Vertisols, we obtained positive SOC sequestration rates when “permanent crops” changed to “arable land”. These are fertile soils usually used for agriculture. Therefore, changes to “arable land” might increase SOC stocks due to land management practices such as inputs of crop residues or nutrients like N, which increase organic C contents in agricultural soils (Smith, 2004). Other practices such as conversion from conventional to zero-tillage or reduced tillage agriculture can lead to SOC sequestration in the early years following a change. Previous authors estimated SOC sequestration of 0.2 Mg C ha-^{1} yr^{-1} with reduced tillage and 0.4 Mg C ha^{-1} yr^{-1} with zero-tillage (Freibauer et al, 2004; Smith et al, 2004). However management practices should be maintained in order to retain SOC in the soil (Marland et al., 2004). In Fluvisols, SOC increments are particularly large when “permanent crops” are transformed to “arable land”, with SOC stocks increasing in the upper 25 cm from 3.9^1 to 49.2 Mg ha^{-1}, equivalent to a SOC accumulation of 45.3 Mg ha^{-1} in the 51 years period. “Arable land” includes the following subclasses: non- irrigated land, crops under plastic, irrigated land and rice fields. Fluvisols frequently occur under rice crops, in which nitrogen fertilizers and crop residues inputs enlarge organic C in soils (Bierke et al., 2008). Therefore, SOC increments in Fluvisols may be a result of the transformation of marginal crops (included in the CLC class “permanent crops”) to rice fields. The transformation of “arable land” to “heterogeneous agricultural areas” resulted in positive SOC sequestration rates in most soil groups (Arenosols, Calcisols, Cambisols, Fluvisols and Luvisols) with a maximum rate of 97% in Luvisols. The CLC class “heterogeneous agricultural areas” consists of a large variety of land uses, including complex cultivation patterns, associations of agriculture land and natural areas and agro-forestry areas. In Andalusia, the main land use within “heterogeneous agricultural areas” is the agro-forestry system *dehesa*, which plays an important role since it represents an ecosystem unique in the world (Romanya et al, 2007). These areas come from the original Mediterranean forest, consisting of pastureland and tree species belonging to the genus *Quercus* (oak), and they have been transformed by traditional human activities related to the agrosylvopastoral use. Nowadays, different studies are being developed to determine the contribution of the *dehesa* to C sequestration and preliminary results indicate a large capacity of these areas for soil C accumulation (Roig and Rubio, 2009), however, further studies are needed in order to establish accurate rates.

Afforestation has been strongly supported by European funds and extensively practiced in Mediterranean areas (Stoate et al., 2009). Land use changes in Southern Spain from agricultural classes to forest types showed different sequestration rates depending on the original agricultural use. Transformations from “arable land” to “forest” lead to an increase of SOC stocks in Regosols and Cambisols (17% and 69% respectively), and a decrease of 33% in Fluvisols. Changes from “heterogeneous agricultural areas” to “forest”, lead to negative sequestration rates in most of the soil groups (Arenosols, Calcisols, Cambisols, Fluvisols and Leptosols). In the 51 years period between 1956 and 2007, a substantial area of Andalusia has changed from “scrub” to “forest”, approximately 535,400 ha (Muñoz-Rojas et al., 2011), with diverse implications for SOC sequestration. Whereas these transformations increased carbon stored in Calcisols and Cambisols (46 and 25% respectively), they induced C losses in Arenosols, Fluvisols, Regosols and Vertisols). Although an increase of SOC stocks after forest plantation could be expected, it should be noted that the CLC class “forest” includes a variety of forest type classes. It has been proved that the tree type affects considerably the SOC stock capacity after forest plantation. For example, coniferous species (pine forests) have remarkably lower capacity to store SOC than broad leaved forest such as oaks (De Vries et al., 2003). Furthermore, it is still uncertain how SOC sequestration under afforestation is affected by the soil type, since many factors are involved; mainly litter production and organic matter decomposition (Paul et al., 2002; Vejre et al., 2003). Some studies reported higher SOC sequestration rates in fertile and clayey soils because of the higher litter production, whereas in other researches poor mineral soils stored more C due to the slow decomposition (Jandl et al., 2007). In general, “deforestation” implied important SOC losses (above 50%) in Cambisols, Luvisols and Regosols. The conversion of “scrub” to “open spaces”, mainly as a result of fire processes have severely affected SOC stocks in the area, mostly in Luvisols and Vertisols.

It should be noted that C stocks in “afforestation” are mostly accumulated in the upper layers of the soil profile, i.e. Leptosols, Luvisols and Regosols, whereas extensification of agriculture increased significantly the SOC contents in deeper layers, i.e. Calcisols , Cambisol, Leptosols, Luvisols.

3.4.3 Comparison with other studies and limitations of the methodology

Several studies of SOC stocks following LULCC have been carried out in Europe, (Bradley et al., 2005; Eaton et al. 2008; Martin et al., 2011; Novara et al., 2012; Wellock et al., 2011), although very few works have been undertaken in the Mediterranean region. Field-based measurements of SOC changes are scarce and limited by high spatial variability of SOC stocks at different scales (Schrumpf et al, 2011). These methodologies are particularly difficult to implement in the Mediterranean area, on account of the great diversity of soil types and land use changes of this region (Romanya et al, 2007).One of the most comprehensive analyses of land use change influence on SOC stocks was conducted by Guo and Gifford (2002). They reported the results of a meta analysis of data derived from 74 publications. Nevertheless, they indicated in their study the need for a more complete analysis due to the lack of data in certain regions.

In this research, the impact of land use changes during a 51-year period in SOC stock changes and SOC sequestration rates has been evaluated. An approach based on the analysis of detailed soil databases containing data of 1357 soil profiles, the soil map of Andalusia, and the LULCMA for the years 1956 and 2007 is followed. The LULCMA for years 1956 and 2007 at scale 1:25,000 comprised a more detailed database than CORINE land cover data (scale 1:100,000), although it is essential to reclassify into the European CORINE nomenclature. Thus, the proposed methodology is easily applicable to other countries, participants in CLC. Several environmental factors are related to SOC such as topography or climate, and might have affected SOC stock changes between 1956 and 2007. Previous research in southern Spain reported significant correlations of winter and summer temperature with Cambisols, Luvisols and Fluvisols (Muñoz-Rojas et al., 2012). In the same study, elevation was significantly correlated to Vertisols. However, in this study we focus on changes in SOC contents following land use changes, which have proved to play a major role in Mediterranean systems (Fantappiè et al., 2011).

Limitations of this methodology could be attributed to the use of the second level of CORINE land cover legend. At this level, groups are heterogeneous (i.e “forest” or “heterogeneous agricultural areas”) and land use change processes are not described in detail. However, this level of classification, corresponding to physical and physiognomic entities at scales 1:500,000 and 1:1,000,000 is adequate for the purpose of this research and data availability. Furthermore, the period considered in this research for the land use change analysis (1956-2006) is representative of long-term periods; however, it would be helpful to study short term periods as well. For example, in the afforestation process, SOC stocks may vary depending on the time of establishment of the plantations and the rate of C decomposition.

3.5 Conclusions

This study comprises the first comprehensive analysis of the impacts of land use changes on SOC stocks at a regional scale in Andalusia (S Spain). In this research, SOC sequestration rates are estimated for different soil groups and land cover flows during a

51-year period, providing baseline information for future studies on C emissions, soil organic C modelling and mitigation scenarios associated with the land-use change processes.

Intensification of agriculture between 1956 and 2007 has resulted in a general decrease of SOC stocks in Andalusia. Soils like Arenosols have been largely affected by these transformations, in particular with changes from “arable land” to “permanent crops”. Remarkable positive rates of change of SOC stocks have been found in Fluvisols and Luvisols with conversion to “arable land” or “heterogeneous agricultural areas”. In these cases, increases might be a result of land management practices such as inputs of crop residues or nutrients, which favour soil functioning in agricultural soils. In order to sustain SOC accumulation, conservative practices should be maintained. In general, afforestation practices contributed to increase SOC, mostly in the topsoil (first 25 cm) although different trends were found for different soil groups. In total, “forest” contributed to the sequestration of 8.62 Mg ha^{-1} of SOC (with a sequestration rate of 25.4%) in the study area. The converse process (“deforestation”) implied important SOC losses (above 50%). in Cambisols, Luvisols and Regosols. Transformation from “scrub” to “open spaces”, have severely affected SOC contents in Andalusia, mostly in Luvisols and Vertisols.

In the last 50 years, land use changes in southern Spain have led to a SOC loss of 16.8 Tg, which indicates an average C sequestration rate of approximately 0.33 Tg year^{-1}. The potential of C sequestration in soils is finite in capacity and time and more research is necessary before confirming SOC sequestration processes as a long-term solution to reduce atmospheric CO_2 levels. However, SOC sequestration could make some contributions to climate change mitigation in the short- or medium-term. On the other hand, this important ecosystem service is linked to soil quality, and it implies positive impacts on soil physical properties such as structure, reduced soil erosion risk, better water infiltration rates, water retention capacity and general soil functioning.

The outcome of this study might be useful to support decision-making in land management and adaptation strategies.

Table S3.1. Soil organic carbon content from Arenosols, Calcisols, Cambisols and Fluvisols (mean and standard deviation; Mg/ha) for each soil group and LU/LUC at different depths (0-25, 25-50 and 50-75 cm). N: number of soil profiles.

Land use change	**Arenosols**				**Calcisols**				**Cambisols**				**Fluvisols**			
	N	**0-25**	**25-50**	**50-75**	**N**	**0-25**	**25-50**	**50-75**	**N**	**0-25**	**25-50**	**50-75**	**N**	**0-25**	**25-50**	**50-75**
Arable land to permanent crops	1	9.3	3.8	1.23	7	33.0 ± 18.1	23.9 ± 13.3		5	25.0 ± 7.5	14.4 ± 8.5	12.5 ± 7.4				
Arable land to heterogeneous agricultural	1	28	28		14	35.8 ± 19.6	32.8 ± 19.3	15.2 ± 11.3	1	25.5	12.5	11.3	1	11.7	32.3	32.3
Arable land to forest									1	43.7	15.4	15.4	1	13.4	13.4	13.41
Arable land to scrub					2	33.3 ± 4.5	30.9 ± 1.3	16.8 ± 3.8	1	41.2			3	30.9 ± 15.8	22.5 ± 9.6	
Permanent crops to arable land	1	12.1	20.5	4.5	22	30.3 ± 19.7	26.1 ± 14.4	23.6 ± 15.4	8	42.4 ± 38.1	17.8 ± 8.2	13.2 ± 5.1	1	49.2		
Permanent crops to heterogeneous agricultural					1	49.1	21.7									
Heterogeneous agricultural to forest	3	21.4 ± 2.3	10.1 ± 10.8	22.3	2	47.8 ± 55.7			7	8.9 ± 5.6	4.1 ± 2.0	0	4	6.7 ± 3.9	6.0 ± 4.5	5.6
Heterogeneous agricultural to arable land	2	27.7 ± 27.6	17.3	6.1	1	44.7	21.6		3	16.6 ± 13.1	16.7 ± 14.9	10.9 ± 7.8				
Heterogeneous agricultural to permanent crops									1	42.1	17.1	10.5				
Heterogeneous agricultural to scrub					1	33.4			1	25.3	25.3					
Forest to heterogeneous agricultural	1	42.1	30.8	19.4	2	47.9 ± 17.8	35.3 ± 25.8	18.5	4	3.5 ± 2.2	1.7 ± 1.7	0.98 ± 1.1				
Forest to scrub	5	34.4 ± 14.5	14.3 ± 1.9	13	1	78.9			2	27.8 ± 30.1						
Forest to arable land													2	23.8 ± 24.1	19.3 ± 17.8	17.4 ± 15.0
Forest to permanent crops					1	23.9			1	3.8						
Scrub to arable land	1	13.9			4	59.5 ± 23.1	19.2		1	22.8	13	5.4	2	17.7 ± 16.7	32.2 ± 2.5	36.1
Scrub to permanent crops	1	6.2	6.2	10.3	1				1	41.3	31.5	29				
Scrub to heterogeneous agricultural	1	3	1.7						5	23.9 ± 20.0	15.4 ± 18.5	15.4 ± 14.1	5	45.7 ± 30.3	35.5 ± 26.1	26.0 ± 21.0
Scrub to forest	6	26.4 ± 15.7	26.7 ± 15.2	24.2	1	87.6	38.5		11	26.0 ± 36.5	17.8 ± 37.5	5.3 ± 5.1	1	9.2		

Table S3.2. Soil organic carbon content from Leptosols, Luvisols, Regosols and Vertisols (mean and standard deviation; Mg ha^{-1}) for each soil group and LU/LUC at different depths (0-25, 25-50 and 50-75 cm). N: number of soil profiles.

Land use change	**Leptosols**				**Luvisols**				**Regosols**				**Vertisols**			
	N	**0-25**	**25-50**	**50-75**	**N**	**0-25**	**25-50**	**50-75**	**N**	**0-25**	**25-50**	**50-75**	**N**	**0-25**	**25-50**	**50-75**
Arable land to permanent crops	3	29.9 ± 1.9	13.4		5	22.45 ± 8.1	23.5 ± 5.1	18.8 ± 6.0	13	37.0± 33.7	22.0 ± 17.3	17.8 ± 17.9	6	27.3 ± 14.9	17.8 ± 3.9	27.1 ± 23.7
Arable land to heterogeneous agricultural	3	41.3 ± 31.1	9.1		2	40.0 ± 2.6	36.8 ± 2.4	34.7 ± 6.0	5	25.8 ± 15.9	27.2 ± 14.7	12.9 ± 10.0	18	34.4 ± 15.7	24.2 ± 12.8	25.3 ± 6
Arable land to forest									1	70.1	3.3					
Arable land to scrub	1	47.7			1	47.9	21.7		6	48.8 ± 38.1	28.9 ± 22.1	21.0 ± 2.5	3	9.1 ± 3.6	5.7 ± 1.8	6.5
Permanent crops to arable land	3	22.1 ± 7.5	19.2 ± 2.9		1	18.5	10.9	16.7	7	27.5 ± 12.9	22.1 ± 8.0	29.2 ± 19.7	2	32.0 ± 19.4	25.9 ± 23.1	27.7
Permanent crops to heterogeneous agricultural									1	22.8	13.8					
Heterogeneous agricultural to forest	8	11.0 ± 5.1	5.8 ± 6.6	2.2 ± 0.5					8	26.1 ± 39.2	18.6 ± 42.4	29.8 ± 56.4				
Heterogeneous agricultural to arable land									3	28.8 ± 16.0	22.2 ± 18.2					
Heterogeneous agricultural to permanent crops	2	16.0 ± 11.1	11.0 ± 4.2	4.1 ± 5.7	4	16.6 ± 13.7	5.0 ± 4.5	3.4 ± 5.0	2	16.5 ± 3.1	9.0 ± 7.7	14.5				
Heterogeneous agricultural to scrub	4	34.0 ± 33.0			2	16.6 ± 17.1	6.9 ± 4.4	6.1 ± 4.7	3	9.4 ± 12.6	1.3 ± 1.1					
Forest to heterogeneous agricultural	7	37.9 ± 31.9	27.1		2	6.0 ± 0.3	4.3 ± 1.5	2.5 ± 1.2	3	9.1 ± 11.0	2.0 ± 0.1	1.7 ± 0.3				
Forest to scrub	4	54.4 ± 53.1	29.5 ± 22.8		1	2.4	1.2	1.6	4	21.3 ± 33.0	3.1 ± 0.1	3.2				
Forest to arable land									2	22.9 ± 21.0	10.4	3.4				
Forest to permanent crops	3	49.8 ± 16.1	32.1						1	5.4	5.4	5.4				
Scrub to arable land	1	29.5			4	17.7 ± 17.0	7.3 ± 7.8	8.8 ± 11.2	5	25.9 ± 19.6	24.2 ± 17.9	20.7 ± 13.2	1	26.3	23.1	22.3
Scrub to permanent crops	4	19.3 ± 18.5	3.7 ± 0.5	3.1	2	87.1 ± 26.5	10.8	9.7	4	26.2 ± 14.0	25.0 ± 29.6	1.5				
Scrub to heterogeneous agricultural	7	20.7 ± 24.3	5.2 ± 4.7	1.6	1	20.7	27		6	32.4 ± 18.8	13.7 ± 14.5	6.9 ± 9.7				
Scrub to forest	45	40.6 ± 38.7	19.3 ± 35.0	2.7 ± 0.7	10	52.8 ± 42.5	21.8 ± 15.1	16.8 ± 13.1	30	29.0 ± 32.3	17.2 ± 23.1	7.3 ± 14.3				
Scrub to open spaces	4	15.4 ± 13.4							2	3.6 ± 0.1	0.1					

Table S3.3. Soil organic carbon content (mean and standard deviation, SD; Mg ha^{-1}) between 0 and 75 cm, and C sequestration rate (CSR, %) for different soil groups (Arenosols, Calcisols, Cambisols and Fluvisols) and LU/LUC. N: number of soil profiles.

Land use/ land use change	Arenosols		Calcisols		Cambisols		Fluvisols		Leptosols		Luvisols		Regosols		Vertisols	
	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD
Arable land, no change																
Arable land to permanent crops	1	39.2	49	70.1 ± 40.3	32	44 ± 47.1	21	60.3 ± 27.7	12	65.1 ± 53.5	21	56.6 ± 45.2	36	62.5 ± 34.8	30	73 ± 32.6
Arable land to heterogeneous agricultural	1	14.4	7	53.5 ± 17.2	5	51.8 ± 17.8			3	34.3 ± 7.4	5	64.8 ± 7.7	13	68.3 ± 51.8	6	64.8 ± 26.1
Arable land to forest	1	56	14	70.4 ± 42.5	1	49.3	1	76.2	3	44.4 ± 26.6	2	111.45 ± 5.8	5	55.3 ± 32.2	18	70 ± 32.8
Arable to scrub					1	74.5	1	40.2					1	73.4		
Permanent crops, no change			2	81 ± 2.1	1	41.2	3	53.4 ± 23	1	47.7	1	69.7	6	84.8 ± 58.4	3	17 ± 8.8
Permanent crops to arable land	3	29.1 ± 41.7	42	64.5 ± 38.4	16	56.4 ± 36	1	10.6	12	35.4 ± 25.4	20	59.9 ± 47.6	42	57.8 ± 33.5	8	58.7 ± 26.8
Permanent crops to Heterogeneous agricultural	1	37.1	22	61.3 ± 41	8	66.2 ± 40.2	1	49.2	3	34.9 ± 17.6	1	46.1	7	54.7 ± 22.2	2	71.8 ± 62.2
Heterogeneous agricultural, no change			1	70.8									1	36.6		
Heterogeneous agricultural to forest	6	44 ± 37.9	8	79.5 ± 60.5	63	22 ± 30.2	10	31.8 ± 45.5	45	21.3 ± 29.4	22	17.8 ± 26.2	16	42.4 ± 48.6	2	7.6 ± 0
Heterogeneous agricultural to arable land	3	39 ± 24.2	2	47.8 ± 55.7	7	13.1 ± 7.2	4	14.1 ± 8.8	8	14.5 ± 10.1			8	57.3 ± 117.1		
Heterogeneous agricultural to permanent crops	2	42.5 ± 37.7	1	66.3	3	44.2 ± 35.7							3	51 ± 17.1		
Heterogeneous agricultural areas to scrub					1	69.7			2	31.1 ± 9.6	4	25 ± 20.7	2	32.8 ± 21		
Forest, no change			1	33.4	1	50.5			4	34 ± 33	2	29.5 ± 26.2	3	10.7 ± 11.4		
Forest to heterogeneous agricultural	17	36.2 ± 19.5	7	69.3 ± 35.3	36	61.9 ± 59.7	10	41.7 ± 29.5	85	39.2 ± 51.2	24	55.7 ± 65.9	68	60.7 ± 63.9		
Forest to scrub	1	92.2	2	92.4 ± 56.6	4	5.9 ± 4.5			7	41.8 ± 36.1	2	12.7 ± 2.4	3	11.5 ± 8.9		
Forest to arable land	5	42.7 ± 17.1	1	78.9	2	27.8 ± 30.1			4	76.6 ± 51.1	1	5.1	4	23.6 ± 31.8		
Forest to permanent crops							2	60.5 ± 56.9			1	68.5	2	29.8 ± 11.3		
Scrub, no change			1	23.9	1	9.8			3	60.5			1	16.3		
Scrub to arable land	11	49 ± 39	8	86.5 ± 42	33	34.8 ± 31.7	5	79.9 ± 47.6	79	45.7 ± 45.4	11	96.7 ± 67.7	47	63 ± 55.6	4	69
Scrub to permanent crops	1	13.9	4	64.2 ± 17.8	1	41.3	2	68.02 ± 39.7	1	29.5	4	31.6 ± 33.4	5	58.4 ± 48	1	71.7
Scrub to heterogeneous agricultural	1	22.7	1		1	101.9			4	21.9 ± 15.5	2	97.3 ± 12	4	45.4 ± 39.9		
Scrub to forest	1	5.5			5	48.5 ± 46	5	96.8 ± 63.9	7	23.9 ± 25.4	1	41.4	6	46.1 ± 32.8		
Scrub to open spaces	6	43.8 ± 36	1	126.1	11	43.4 ± 73.2	1	9.2	45	46 ± 48.9	10	86.3 ± 61.6	30	45.1 ± 51.9		
									4	15.4 ± 13.4			2	4 ± 0.2		

CHAPTER 4

ORGANIC CARBON STOCKS IN MEDITERRANEAN SOIL TYPES UNDER DIFFERENT LAND USES (SOUTHERN SPAIN)

4.1 Introduction

Soil organic C plays an important role in the global C cycle. It is generally assumed that soils are the largest C sinks in terrestrial ecosystems. Soils act as a source or a sink of atmospheric CO_2 and contain approximately twice the amount of C in the atmosphere, and about three times the amount in vegetation (IPCC, 2000, 2007, Lal, 2004). Soils have the ability to store C for long periods of time; thus, changes in the size of the soil C pool could significantly modify the atmospheric CO_2 concentration. Additionally, an adequate level of SOC stock is essential to decrease erosion and degradation risks, hold water and nutrients and improve soil structure (Lal, 2004). Carbon sequestration is a crucial strategy for reducing atmospheric CO_2 concentration, contributing to climate change mitigation (Lal, 2003). Globally, soil C pools contain approximately 1,550 Gt of organic C in the top 1 m (from a total of approximately 2,500 Gt C), and SOC sequestration is estimated at 0.4 to 1.2 Pg C year $^{-1}$, equivalent to 6-20% of the annual release from fossil fuel combustion (Lal, 2004; Houghton, 2005). On the other hand, the soil C pool is particularly difficult to quantify and in some cases it is assumed to be a fixed fraction or ignored due to lack of data or precise methodologies. During the last years, the need for accurate information on SOC content at the European, national or regional level has increased due to the importance of SOC stocks for sustainable use of natural resources. In addition to the present concern about environmental problems such as soil degradation and soil contamination, information on SOC stocks is necessary to assess the potential role of soils as CO2 sinks. Reports of national inventories of C stocks are required under the Kyoto Protocol by the United Nations Framework Convention on Climate Change, to estimate C emissions to the atmosphere, which requires accurate and reliable estimates of current C stocks. Carbon inventories and analysis of SOC distribution constitute an essential tool for modelling the effects of different factors involved on SOC sequestration potential.

Soil organic C pools at global scales are difficult to assess due to high spatial variability and different factors affecting soil C dynamics. Among these factors, land use has a strong influence on SOC stocks (Liebens and VanMolle, 2003; Meersmans et al., 2008; Smith, 2008), altering the balance between C losses and sequestration (Ostle et al., 2009). Nevertheless, there are further determinants influencing SOC variability, such as climate and topography (Phachomphon et al., 2010; Schulp et al., 2008). Consequently, SOC estimates are commonly uncertain in areas with heterogeneous land uses and a high variety of climate and site patterns (Leifield et al., 2005) such as the Mediterranean environments. At the same time, soil depth has an important influence on SOC stocks (Grüneberg et al., 2010). Most studies on SOC are restricted to the topsoil, although vertical processes have a considerable effect on SOC variability (VandenBygaart, 2006).

The few existing studies that compare the dynamics of SOC in the upper horizons and the subsurface, suggest a variation in depth of factors controlling SOC dynamics, a hypothesis that has not yet been thoroughly investigated (Albadalejo et al., 2011; Salome et al., 2010). Vertical distribution is one of the features of the organic C pool that is not clearly understood together with the relationships with climate and vegetation (Jobbágy and Jackson, 2000).

Several studies have estimated SOC stocks on a large scale by using national and global soil maps and a certain amount of representative soil profiles, or by combining soil and land cover spatial datasets (Arrouays et al., 2001; Batjes, 1996; Batjes 2005; Batjes and Dijkshoorn, 1999; Bradley et al., 2005; Leifeld et al., 2005; Morisada et al., 2004). Commonly, inventories are based on a combination of soil-land use mapping units and assignment of mean SOC values from soil profiles, which makes it possible to determine patterns in SOC variability related to soil and land use features. However, the reliability of these estimates depends upon the quality and resolution of the land use and soil spatial databases. Moreover, due to the large spatial variability of SOC within the map units, an elevated density of soil sampling points is required to achieve accurate estimates (Liebens and VanMolle, 2003; Martin et al., 2011). According to Bahn et al (2009), a key item in future research in the terrestrial C cycle is an accurate assessment of SOC pool in ecosystems and regions that have so far been heavily under-represented. Whereas the SOC pool has been studied at global, continental (Eswaran et al., 1993, Liski et al., 2002; Smith, 2004) or regional scales in humid forest systems (Batjes and Dijkshoorn, 1999; Schwartz and Namri, 2002), there is a lack of information on Mediterranean systems. In addition, estimates of SOC stocks may be particularly inaccurate in areas with diverse land use patterns, such as Mediterranean landscapes. In Spain, for example, Rodriguez-Murillo (2001) assessed organic C contents under different types of land use and soil. Nevertheless, there are few studies providing accurate regional SOC estimates based on combined studies of soil land cover data. In general, there is a lack of national-scale studies on soil spatial variability in Spain (Ibáñez et al., 2005) and therefore detailed studies on SOC distribution in soils are necessary (Flores et al., 2007). Future studies on SOC pools need to be carried out in a comparable way, and the access to datasets needs to be facilitated (Bahn et al., 2009). This study comes to fill a gap in SOC assessment in Mediterranean soils.

The objectives of this study are [1] to quantify current SOC contents and SOC stocks in Andalusia (S Spain) for each land use and soil group at different soil depths, [2] to assess possible relationships between SOC stocks and environmental variables, and [3] to elaborate a SOC map of the studied area. The Mediterranean area represents an important challenge to scientists and land managers because of its size, physical complexity, geological and anthropological history (Blondel and Aronson, 1995). The information generated in this study will be a useful basis for modelling SOC processes and designing of management strategies for stabilizing the increasing atmospheric CO_2 concentrations by preservation of C stocks and sequestration in other Mediterranean regions.

4.2 Materials and methods

4.2.1 Origin of data and treatment

Soil data

Data from 1479 geo-referenced selected soil profiles reported and described by Jordán and Zavala (2009) and the SEISnet soil database (http://www.evenor-tech.com/banco/seisnet/seisnet.htm) distributed through the study area have been used to estimate SOC content. These databases contain descriptive and analytical data, including site characteristics, horizon description, chemical and physical analysis. Selection of soil profiles was carried out considering homogeneous sampling and analysis methods. Variables used in this study were soil depth (cm), organic C content (g 100 g^{-1} soil), bulk density (g cm^{-3}) and coarse fragments (mineral particles >2 mm in diameter). Soil reference groups were described and classified according to FAO (2006). Organic C was determined by dichromate oxidation using the Walkley-Black method (Walkley and Black, 1934). Bulk density was measured by the core method (Blake and Hartge, 1986). In order to normalize information from soil profiles, data were re-coded and imported to the SDBm Plus Multilingual Soil Profile Database, a geo-referenced soil attribute database that contains a large number of descriptive and analytical data fields (De la Rosa et al., 2002). As soil profiles showed a range of depths, data were homogenised and re-sampled for 0-25, 25-50 and 50-75 cm. The SDBm Plus database incorporates a “control section” function, which allows determining the thickness of the layer to be analysed within the soil profile. This function allows calculating the weighted average value for each variable in standard control sections.

The spatialization of soil data was carried out following the spatial distribution of soil groups from the soil map of Andalusia (CSIC-IARA, 1989) at scale 1:400,000, which contains 2,707 polygons classified in 64 soil map units, according to the legend of the soil map of the world (IUSS Working Group WRB, 2006).

Climate data

Climate data were obtained from the time series of the CLIMA subsystem of the Environmental Information Network of Andalusia (REDIAM, Andalusian Regional

Government) which integrates several databases from a set of over 2200 observatories since 1971. Selected variables were mean annual temperature and mean annual precipitation.

Elevation and slope

Elevation and slope data were extracted from the 100 m resolution digital elevation model (DEM) of Andalusia (ICA, 1999) derived from the topographic map of Andalusia (S 1:10,000).

Land use and land cover data

Land use classification and land cover data for this study were taken from the Land Use and Land Cover Map of Andalusia (LULCMA) for 2007 at scale 1:25,000 and minimum map unit 0.5 ha (Moreira, 2007). More information on these land use datasets is provided in Chapter 2. Land cover classes of LULCMA were reclassified into CLC standard nomenclatures, in order to make the methodology accessible to other CORINE programme member countries and obtain easily comparable outcomes (Muñoz-Rojas et al., 2011).

4.2.2 Soil organic C stock calculation

For each soil layer of the 1479 soil profiles, soil organic C content (SOCC) was estimated as follows:

$$\mathrm{SOCC} = \mathrm{SOC} \times \mathrm{BD} \times \mathrm{D} \times (1\text{-}\mathrm{G}) \qquad (1)$$

where SOCC is soil organic C content (Mg ha^{-1}), SOC is soil organic C percentage (g 100^{-1} g^{-1}), BD is bulk density (g cm^{-3}), D is the thickness of the studied layer (cm) and G is the proportion in volume of coarse fragments. Soil profiles were classified according to original soil profile descriptions, into 10 soil reference groups (IUSS Working Group WRB, 2006): Arenosols, Calcisols, Cambisols, Fluvisols, Leptosols, Luvisols, Planosols, Regosols, Solonchaks and Vertisols, and 7 land use types (following CLC nomenclature at level 2: “arable land”, “permanent crops”, “heterogeneous agricultural areas”, “forest”, “scrub and/or vegetation associations”, “Open spaces with little or no vegetation”, and “maritime wetlands”).

Data analysis was performed using SPSS (SPSS, 2009) and ArcGIS (ESRI, 2006) software packs. To determine SOC for each soil group within every land cover type, the study area was divided into “land use-soil association units” (landscape units) using a topological intersection of the LULCMA for 2007 and the Soil Map of Andalusia. The overlay of both maps resulted in 85,492 new polygons, defined by 1 soil group (dominant unit) and one aggregated land cover type. Mean values of SOCC of each land use-soil association was assigned to all the new polygons. Soil organic C stocks for each soil group were determined by multiplying SOCC mean values by the area occupied by the land use-soil unit in the overlay map.

4.2.3 Relationships between soil organic C content and environmental variables

In order to identify the influence of environmental factors (climate and site factors) on SOC, correlation analyses were performed using Statistica (StatSoft, 2001). The following variables were considered: mean annual precipitation (mm), mean winter (December-February) and summer (June-August), temperature, elevation and slope. Analyses were carried out for the total set of soil profiles, and for different soil reference group and land use classes. A number of soil profiles, classified as Planosols, Solonchaks and soils from "maritime wetlands" were not considered in the analysis because of the absence of SOC variation with environmental variables. Elevation and slope data for each profile was extracted from the DEM, and climate variables (mean annual rainfall and mean summer and winter temperature), were obtained from the Climate Spatial Datasets in raster format. Data Analysis was performed using ArcGIS Spatial Analyst extension tool (ESRI, 2006).

4.3 Results

4.3.1 Soil organic C contents from main land use types and soil groups

The total area of soils under "arable land", "permanent crops", "heterogeneous agricultural areas", "forest", "scrub and/or vegetation associations", "open spaces with little or no vegetation", and "maritime wetlands", identified using the Soil Map of Andalusia and LULCMA, was 83,687 km^2 (Table 4.1). Ten major soil groups occur in the study area. Cambisols (42.7% of the studied area) and Regosols (19.7%) are most common, followed by Vertisols (8.8%), Leptosols (8.6%), and Luvisols (8.3%). These five major groups account for about 73,744.74 km^2 (88.1% of the studied area).

Soil organic C content (SOCC) and coefficient of variation (CV) were calculated for each land use and soil group combination/association in the study area (Table 4.2). Values are shown for 0-25, 25-50, 50-75 and 0-75 cm depths. On average, Calcisols, Regosols and Solonchaks have the highest SOCC values, above 55 Mg C ha^{-1} while Arenosols and Leptosols show the lowest amounts, below 40 Mg C ha^{-1} (Table 4.2, Figure 4.1). Likewise, SOCC is considerably lower in "Open spaces with little or no vegetation" compared to the other land use types, and "maritime wetlands" have the highest SOCC of all land use classes (Table 4.2, Figure 4.2).The highest SOCC values in the first 25 cm of soil were observed in Fluvisols and Solonchaks under "maritime wetlands", which store more than 50 Mg C ha^{-1} (Table 4.2). Calcisols under "heterogeneous agricultural areas" and "forest"

Table 4.1. Area (km^2) and SOC stocks (SOCS, Gg) under main land uses and soil groups.

Soil group	**Arable land**		**Permanent crops**		**Heterogeneous agricultural areas**		**Forest**		**Scrub and/or herbaceous**		**Open spaces with little or no**		**Maritime wetlands**		**Total**	
	Area	**SOCS**	**Area**	**SOCS**	**Area**	**SOCS**	**Area**	**SOCS**	**Area**	**SOCS**	**Area**	**SOCS**	**Area**	**SOCS**	**Area**	**SOCS**
	km^2	**Gg**	**km^2**	**Gg**	**km^2**	**Gg**	**km^2**	**Gg**	**km^2**	**Gg**	**km^2**	**Gg**	**km^2**	**Gg**	**km^2**	**Gg**
Arenosol	75.00	215.39	19.23	62.48	17.66	88.72	158.95	527.60	150.77	655.34	12.40	21.12	43.10	0.00	477.12	1,570.66
Calcisol	418.44	2,754.74	118.92	661.63	323.62	2,659.63	35.34	342.49	823.90	5,463.85	15.52	0.00	1.66	0.00	1,737.40	11,882.35
Cambisol	4,513.96	21,328.30	7,296.52	43,692.96	6.351.18	21,934.10	7,990.29	26,414.11	9,352.92	49,295.52	205.01	0.00	16.21	0.00	35,726.09	162,664.99
Fluvisol	1,454.13	7,969.70	961.37	5,913.48	613.15	3,772.10	435.89	2,054.75	775.91	2,972.40	23.49	0.00	65.62	706.39	4,329.57	23,388.82
Leptosol	255.75	987.41	542.77	1,503.48	352.12	1,322.69	1,755.01	7,191.84	4,175.28	16,872.29	91.67	408.71	0.00	0.00	7,172.58	28,286.40
Luvisol	1,522.38	8,086.08	2,389.15	13,689.13	866.75	4,422.00	982.42	5,844.76	1,193.73	6,090.40	20.50	0.00	8.81	0.00	6,983.74	38,132.36
Planosol	722.15	4.221.14	416.67	0.00	171.06	0.00	374.67	0.00	206.29	521.61	9.20	0.00	16.15	0.00	1,916.20	4,742.75
Regosol	2,040.71	12,991.90	3,888.70	19,577.74	1.637.16	6,809.04	3,616.00	20,088.98	5,150.77	31,849.11	152.03	567.00	32.81	62.16	16,518.18	91,945.94
Solonchak	923.80	1,464.13	11.89	0.00	80.23	0.00	42.91	0.00	64.12	343.75	17.39	0.00	341.36	2,416.86	1,481.70	4,224.74
Vertisol	3,542.16	24,569.57	1,630.43	9,552.42	973.77	7,261.86	519.88	5,132.26	668.29	1,851.86	8.23	0.00	1.39	0.00	7,344.15	48,367.97
Total	15,468.49	84,588.35	17,275.66	94,653.32	11.386.70	48,270.14	15,911.37	67,596.79	22,561.98	115,916.14	555.43	996.83	527.12	3,185.41	83,686.74	415,206.98

Table 4.2. Soil organic C contents (SOC) for land use-soil combinations at different soil depths (0-25, 25-50 and 0-75 cm) (Mg ha^{-1}). N: number of values, M: mean value, CV: coefficient of variation (%), na: insufficient number of samples to provide statistics (not available), nd: not determined because one value only.

Soil group Depth (cm)	Arable land			Permanent crops			Heterogeneous agricultural areas			Forest			Scrub and/or herbaceous vegetation associations			Open spaces with little or no vegetation			Maritime wetlands			Total		
	N	SOC	CV	N	SOC	CV	N	SOC	CV	N	SOC	CV	N	SOC	CV	N	SOC	CV	N	SOC	CV	N	SOC	CV
Arenosol																								
0-25	5	18.6	94.51	6	16.4	84.8	1	34.1	33.9	2	25.8	58.2	2	29.9	78.1	2	16.2	126.7	0	na	na	71	26.5	67.1
25-50		3.5	101.3		15.2	107.		10.3	75.5		5.2	151.3		8.3	173.6		0.8	141.4		na	na		7.3	150.1
50-75		0.05	175.2		0.95	189.		5.9	135.6		2.2	224.8		5.3	181.2		0.0			na	na		3.8	199.9
Total		22.1	70.2		32.5	91.6		50.2	33.9		33.2	57.3		43.5	95.8		17.0	127.4		na	na		37.7	74.6
Calcisol																								
0-25	8	35.5	53.82	5	29.15	62.8	7	50.1	65.5	2	50.7	57.7	1	45.9	56.6	0	na	na	0	na	na	18	36.9	61.7
25-50		23.3	84.4		18.7	89.6		25.5	62.6		27.5	58.8		19.2	113.6		na	na		na	na		22.2	83.0
50-75		7.0	179.3		7.9	183.		6.6	175.5		15.7	101.7		1.2	374.2		na	na		na	na		8.0	169.4
Total		65.8	56.8		55.6	65.1		82.2	42.3		96.9	46.0		66.3	62.4		na	na		na	na		67.6	59.4
Cambisol																								
0-25	5	19.6	94.7	1	30.2	39.1	3	22.6	86.8	9	19.3	137.1	3	30.7	104.9	0	na	na	0	na	na	23	22.2	110.1
25-50		16.3	98.3		18.3	63.9		8.3	113.1		8.9	151.9		15.5	136.5		na	na		na	na		12.0	126.5
50-75		11.4	121.2		11.4	78.7		3.7	187.8		4.9	210.8		6.6	160.6		na	na		na	na		6.8	162.2
Total		47.3	91.7		59.9	46.4		34.5	89.4		33.1	143.6		52.7	97.9		na	na		na	na		41.1	108.9
Fluvisol																								
0-25	2	26.7	68.5	1	29.5	nd	1	29.9	66.8	1	19.3	120.3	1	26.9	103.5	0	na	na	1	73.6	nd	73	26.3	84.0
25-50		20.8	71.8		32.0	nd		21.7	65.3		18.3	117.8		5.8	118.7		na	na		20.3	nd		17.9	90.9
50-75		7.3	167.4		0.0	nd		9.9	135.9		9.6	153.8		5.6	221.3		na	na		13.7	nd		8.0	160.4
Total		54.8	53.0		61.5	nd		61.5	61.3		47.1	118.1		38.3	92.0		na	na		107.	nd		52.1	75.6
Leptosol																								
0-25	1	27.7	98.9	1	20.2	82.5	5	33.6	97.6	1	33.6	111.0	1	34.5	100.3	2	44.6	122.0	0	na	na	33	33.1	104.7
25-50		9.1	158.4		5.5	144.		3.9	269.4		6.3	350.6		4.9	257.8		0.0			na	na		5.6	304.5
50-75		1.8	435.9		2.1	195.		0.0	734.9		1.1	512.7		0.9	471.8		0.0			na	na		0.9	512.8
Total		38.6	94.3		27.7	67.0		37.6	94.3		41.0	126.3		40.4	100.2		44.6	122.0		na	na		39.6	111.2
Luvisol																								
0-25	3	25.1	82.6	3	25.6	70.7	1	24.8	143.3	4	33.9	103.1	2	28.7	132.1	0	na	na	0	na	na	14	28.2	104.7
25-50		17.8	93.4		18.5	80.3		15.3	174.7		15.2	107.8		15.1	128.8		na	na		na	na		16.5	107.9
50-75		10.2	124.5		13.3	99.8		11.0	227.6		10.4	115.1		7.3	191.9		na	na		na	na		10.5	137.7
Total		53.1	78.45		57.3	73.8		51.0	152.7		59.5	100.5		51.0	127.7		na	na		na	na		55.2	100
Planosol																								
0-25	2	28.8	22.9	0	na	na	0	na	na	0	na	na	1	17.6	nd	0	na	na	0	na	na	3	25.1	31.8
25-50		16.4	13.0		na	na		na	na		na	na		7.7	nd		na	na		na	na		13.5	39.0
50-75		13.2	7.3		na	na		na	na		na	na		0.0	nd		na	na		na	na		8.8	86.9
Total		58.5	16.6		na	na		na	na		na	na		25.3	nd		na	na		na	na		47.4	42.9
Regosol																								
0-25	5	31.9	66.4	5	24.8	73.2	3	21.5	112.7	1	34.6	87.7	7	35.5	80.9	4	29.9	32.5	1	19.0	nd	32	31.3	84.1
25-50		22.1	70.5		17.8	79.1		12.5	196.5		16.5	131.6		16.9	147.1		7.4	165.9		0.00	nd		17.2	120.8
50-75		9.7	150.6		7.7	162.		7.7	286.3		4.5	198.1		9.4	222.2		0.0			0.00	nd		7.2	211.5
Total		63.7	60.2		50.4	62.6		41.6	153.4		55.6	92.0		61.8	104.7		37.3	46.3		19.0	nd		55.7	92
Solonchak																								
0-25	2	11.1	65.8	0	na	na	0	na	na	0	na	na	8	30.1	44.8	0	na	na	1	50.4	50.5	20	38.4	61.7
25-50		2.1	141.4		na	na		na	na		na	na		17.0	79.1		na	na		17.4	121.		15.7	110.1
50-75		2.6	141.4		na	na		na	na		na	na		6.5	163.7		na	na		3.0	290.		4.3	207.2
Total		15.9	3.79		na	na		na	na		na	na		53.6	60.0		na	na		70.8	49.8		58.4	60.5
Vertisol																								
0-25	5	28.3	48.69	1	25.2	54.8	2	38.5	8.5	5	42.4	18.9	7	13.1	127.9	0	na	na	0	na	na	78	27.6	53.3
25-50		23.0	57.1		17.8	54.3		31.3	24.8		35.9	25.7		8.9	146.9		na	na		na	na		21.9	61.1
50-75		18.1	81.7		15.7	67.4		4.8	141.4		20.4	64.1		5.7	189.6		na	na		na	na		16.4	85.2
Total		69.4	44.8		58.6	43.3		74.6	3.1		98.7	14.9		27.7	146.3		na	na		na	na		65.8	50.1
Total																								
0-25	3	28.5	69.6	1	26.1	66.2	1	28.7	96	4	39.9	103.8	2	33.1	94.5	8	30.0	83.8	1	49.7	52	14	30.1	91.1
25-50		19.8	84.2		17.3	84.4		10.5	164.4		11.9	167		11.2	168.7		3.9	227		16.2	122		0.1	130.7
50-75		10.0	137.9		8.8	144.		4.7	294.7		4.9	208		4.9	264.8		na	na		3.6	234.		6.5	193.6
Total		58.3	65.4		52.2	65.3		43.8	106.2		47.8	51.9		49.1	103.6		34.1	79.8		69.6	53.5		50.6	91.2

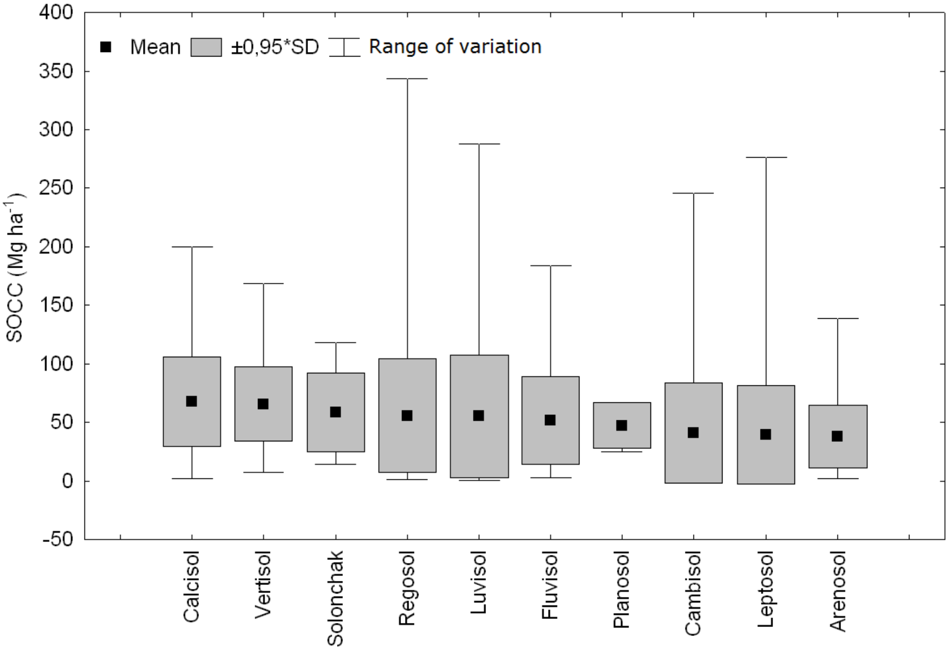


Figure 4.1. Soil organic carbon content (SOCC) for the major soil groups in the study area. SD: standard deviation.

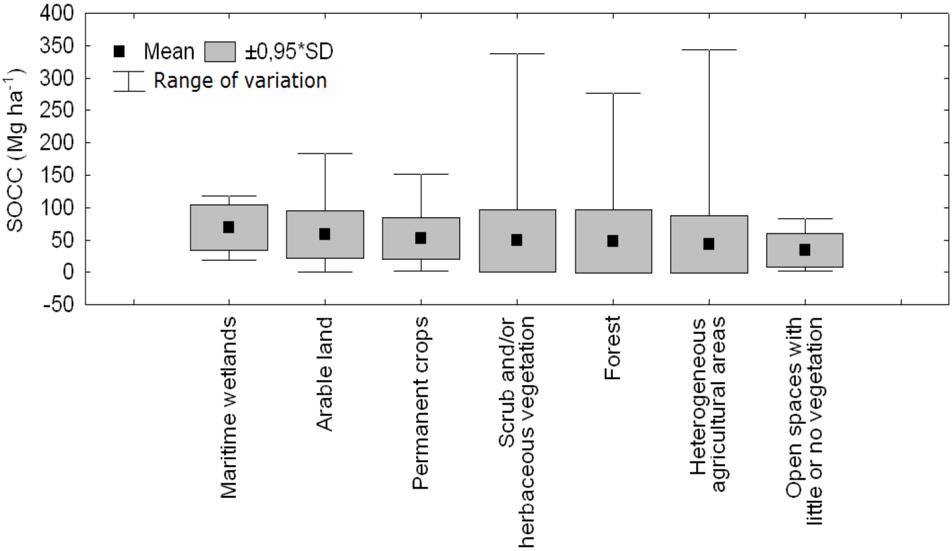


Figure 4.2. Soil organic carbon content (SOCC) for each land use type in the study area. SD: standard deviation.

stored 50.1 and 50.7 Mg C ha^{-1} respectively. Solonchaks under “arable land” and Vertisols under “scrub and/or herbaceous vegetation associations”, have the lowest SOCC values, storing less than 14 Mg C ha^{-1}. The average SOCC distribution with depth is similar in all land use-soil combinations, decreasing rapidly with increasing soil depth and tending to near-zero values below 50 cm for soils under open spaces with little or no vegetation (Arenosols, Leptosols and Regosols). Vertisols and Calcisols under “forest” store high amounts of SOC at larger depths comparing to other soil groups with SOCC values above 27 Mg C ha^{-1} and 15 Mg C ha^{-1} in the layers 25-50 cm and 50-75 cm.Values of SOCC in the entire depth down to 75 cm range between 107.6 Mg C ha^{-1} for Fluvisols under “maritime wetlands” and 15.8 Mg C ha^{-1} for Solonchak under “arable land”. A large variation in SOC exists within each land use-soil association with CV ranging between 3.74% for Solonchaks under “arable land” and 152.67% for Luvisols under “heterogeneous agricultural areas”.

4.3.2 SOC stocks from main land use types and soil groups

Total stocks per land use class and soil group (in absolute terms) are given in Table 4.1. “scrub and /or vegetation associations” contain 115.92 Tg C in 22,561.98 km^2, “permanent crops” 94.65 Tg C in 17275.66 km^2, “arable land” 84.59 Tg C in 15468.49 km^2 and “forest” 67.60 Tg C in 15911.37 km^2. Soils with the largest SOC stock are Cambisols (162.66 Tg), Regosols (91.95 Tg) and Vertisols (48.37 Tg). The estimated SOC stock in the upper 75 cm is 415 Tg (Table 4.1). Accumulated C stocks for each soil group and land use class are shown in Figure 4.3 and Figure 4.4, respectively. All soil groups store more than 50% of total C in the first 25 cm, except Vertisols which accumulates less than 45%. The proportion of SOC stock in the 0-25 cm layer is on average about 55% (229.69 Tg) of the total SOC stock in the upper 75 cm, around 30% (122.89 Tg) in the 25-50 cm layer and 15% (62.62 Tg) in the deepest layer (50-75 cm) (Figures 4.3 and 4.4). Among all land use types, agricultural uses such as “arable land” and “permanent Crops” show low percentages of SOC stock in the first layer (below 50%). Current spatial distribution of SOCC per land use-soil association unit (Mg C ha^{-1}) in Andalusia is shown in Figure 4.5.

4.3.3 Relationships between SOC and environmental data

Statistical analysis of correlations between SOC contents and environmental factors is shown in Table 4.3. Mean values, standard deviation and correlation coefficients have been obtained for each variable and SOC in the total dataset and land use/soil unit groups. Considering all the soil profiles, SOC was negatively correlated with slope ($r = -0.2900$). The analysis did not show significant correlations with other variables.

Table 4.3. Mean soil organic carbon content (Mg ha-1) and standard deviation for each soil and land use type and correlation coefficients between soil organic carbon content and environmental variables. (*) p≤0,05; (**) p≤0,01; (***) p≤0,001. Non-significant correlation coefficients are not marked.

Type	Group	N	Mean	Std.Dev.	Winter Temperature	Summer Temperature	Total precipitation	Elevation	Slope
Soil	Arenosols	71	36.919	8.0129	0.132	0.1115	0.4624	-0.0808	-0.6201
	Calcisols	186	67.772	8.0194	0.0123	-0.6355	0.4861	0.336	0.3494
	Cambisols	238	41.49	12.981	0.9550 *	-0.4089	-0.257	-0.8775	-0.0372
	Fluvisols	73	56.606	30.4507	0.465	-0.8291 *	-0.3751	-0.7219	-0.5153
	Leptosols	337	37.63	15.6144	-0.422	-0.69937	-0.6166	-0.1992	-0.5535
	Luvisols	144	50.703	26.9051	0.8249 *	-0.5144	0.8041	-0.406	0.6917
	Regosols	329	42.573	22.5279	-0.6058	-0.0881	-0.0622	0.2386	-0.199
	Vertisols	78	60.883	10.4383	0.637	0.906	-0.9111	-0.9511 *	0.0175
Land use	Arable land	331	55.196	12.1328	-0.0345	-0.0394	0.13	0.0387	-0.09
	Forest	470	45.212	14.2694	-0.4833	-0.8794 **	0.7908 *	0.6795	-0.0399
	Heterogeneous agricultural areas	169	48.09	21.4989	0.9319 ***	-0.5134	-0.7454 *	-0.8818 **	-0.1654
	Open spaces with little or no vegetation	8	16.963	11.458	-0.0078	-0.8816	-0.8009	-0.6594	-0.6894
	Permanent crops	191	43.122	19.0391	-0.413	0.5452	-0.375	0.044	-0.6657
	Scrub and/or herbaceous vegetation associations	298	55.232	21.8231	-0.2346	-0.0902	0.4386	0.2303	0.5722
All groups		1456	47.988	21.4769	0.1279	-0.261	-0.053	-0.2274	-0.2900 *

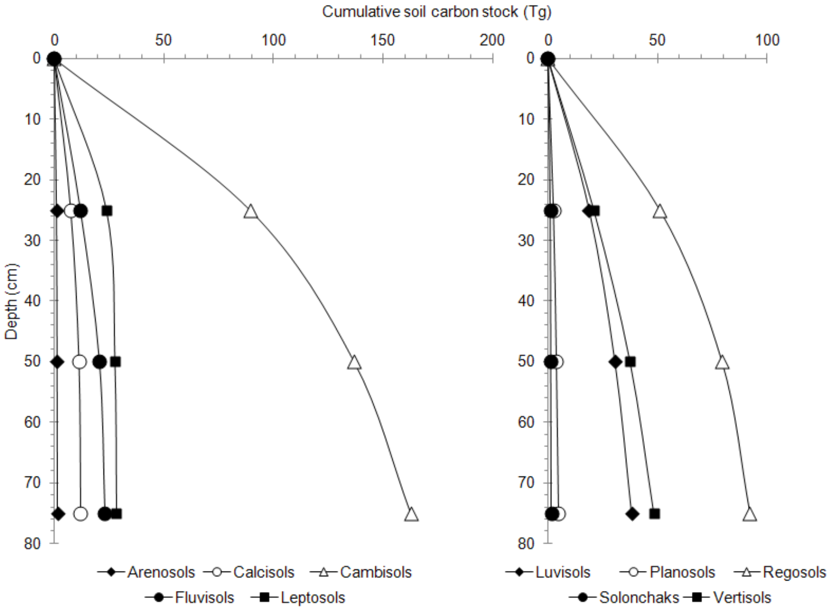


Figure 4.3. Cumulative soil organic carbon stock in depth for each soil group.

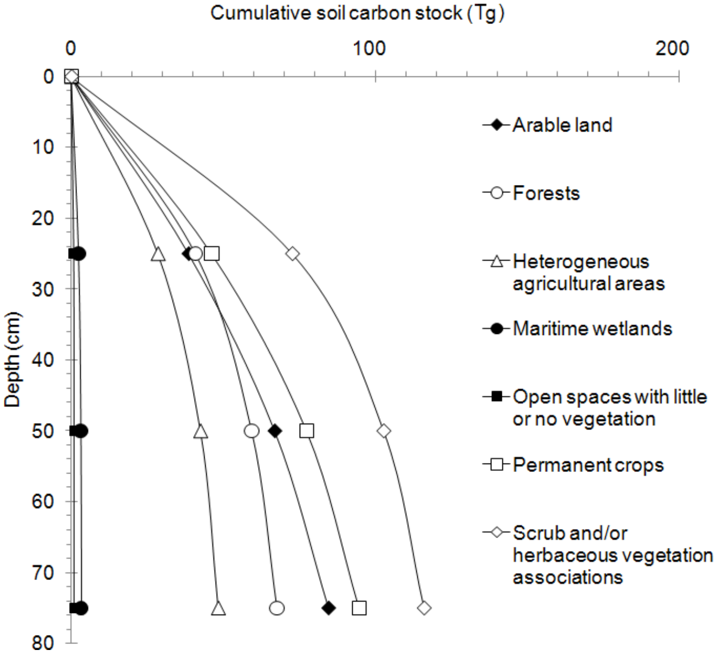


Figure 4.4 Cumulative soil organic carbon stock in depth for each land use type.

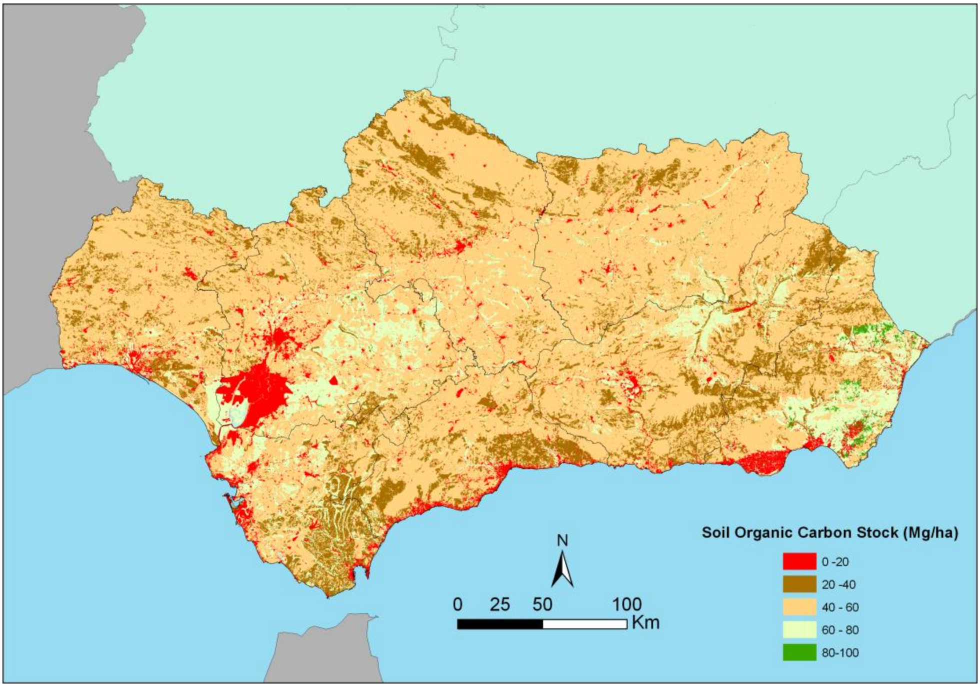


Figure 4.5 Map of soil organic carbon stocks (Mg ha^{-1}) (0-75 cm) in Andalusia.

SOC was positively correlated with summer temperature in Cambisols and Luvisols (r = 0.9550 and r = 0.8249) and negatively correlated with winter temperature (r = -0.8291) in Fluvisols. In Vertisols, a significant negative correlation was found with elevation (r = -0.9511). Among land uses, SOC showed a positive correlation with winter temperature in “heterogeneous agricultural areas” (r = 0.9319) and a negative correlation with summer temperature in “forest”. Elevation is also well correlated with SOC in “heterogeneous agricultural areas” (r = -0.8818)

In both natural land use types (“heterogeneous agricultural areas” and “forest”), significant correlations were found with SOC and annual precipitation. However, whereas in “forest” the correlation was positive (r = 0.7908), in “heterogeneous agricultural areas” SOC was negatively correlated with precipitation (r = -0.7454).

4.4 Discussion

4.4.1 Soil carbon stocks

Studies on the spatial distribution of SOC in relation with soil groups have been carried out by many authors. Liebens and VanMolle (2003), for example, evaluated different methodologies for assessing SOC stock in Flanders, Belgium, in which SOC densities were assigned to polygons on the digital soil map of Flanders. For the total area of Belgium, Lettens et al. (2005) used a topological intersection of CLC geo-data sets and a digitized soil association map and soil C data from different data sets to plot the distribution of soil C stocks in the country. Also, in France, Arraouays et al. (2001) took into account both forest soil types and vegetation cover. Then C densities were determined by soil/land use category using a combination of geo-referenced soil and CORINE land use databases. The same approach was used in Great Britain by Howard et al. (1995), who mapped the geographical distribution of SOC with estimates based on the dominant soil series and land cover class for 1 km × 1 km blocks. Nevertheless, studies concerning both soil type and land use combined data are scarce, especially in Mediterranean areas. Different soil types show a range of capacities for C sequestration due to soil inherent potential (based on texture, mineralogy, etc) to retain organic C (Gibson et al., 2002) and therefore, both soil and land use data should be used in determining soil C stocks.

A number of studies have been carried out in different regions of Spain concerning SOC stocks under main land uses and/or soil types (Boix-Fayos et al., 2009; Diaz-Hernández et al., 2003; Ganuza and Almendros, 2003; Jordán et al., 2007). One of the most complete is the work conducted by Rodriguez-Murillo (2001), in which stock and spatial distribution of SOC in peninsular Spain was determined using soil profile descriptions available in literature. Our estimates are in agreement with the results obtained in Mediterranean areas by other authors. Among the soil groups, the largest average SOCC is found in Calcisols, and Vertisols (Figure 4.1). Most of Calcisols occur under “scrub and/or herbaceous associations” and values of SOC stocks for Calcisols obtained in this research are generally larger than those found by several authors (e.g., Rodríguez-Murillo, 2001). However, determined SOCCs are similar to those estimated by Diaz-Hernandez (2003) in South eastern Spain, with 52 Mg C ha^{-1} at 0.5 m depth and 70 Mg C ha^{-1} at 1 m depth. A high SOC content in Vertisols which are naturally fertile soils may be explained by its high clay content and consequently high moisture storage capacity. Similar values of SOCCs for Vertisols were reported in Spain by Rodríguez-Murillo (2001), 68.9 Mg C ha^{-1}, and in Jordan by Batjes (2006), 37 Mg C ha^{-1} at 0.3 m depth and 75 Mg C ha^{-1} at 1 m depth with 59 Mg C ha^{-1} for “arable land” and 68 Mg C ha^{-1} for “forest” at 1 m depth. Moreover, in Tunisia, Brahim et al. (2010) estimated 45.6 Mg C ha^{-1} at 30 cm depth and 109.7 Mg C ha^{-1} at 1 m depth. Higher values were found in Central and Eastern Europe by Batjes (2002), with 82 Mg C ha^{-1} at 0.3 m and 236 Mg C ha^{-1} at 1 m depth.

A low SOC content is observed for coarse textured Arenosols. However, values encountered in this soil group are above those calculated by Rodriguez Murillo (2001) and Batjes (2006), who estimated SOCCs of 22.2 Mg C ha^{-1} in Spain and 20.0 Mg C ha^{-1} in Jordan respectively. Nevertheless, calculations for SOC stocks estimated for Arenosols in this research are similar to values reported in France by Arrouays et al. (2001) which range between 28 Mg C ha^{-1} under "arable land" to 44 Mg C ha^{-1} under "forest".

Cambisols are the most predominant soil group in the study area together with Regosols (Table 4.2). Cambisols are spread in a wide range of environments around the world and under all types of vegetation. Most of the European Regosols are found in the Mediterranean region and are particularly common in arid areas. In the study area of this research, both soil groups are used for agriculture and show high values of SOCCs under agricultural land uses. We obtained lower SOCCs for Cambisols than those estimated by other authors in other Mediterranean areas such as Spain and Tunisia. In these areas, Rodriguez-Murillo (2001) and Brahim et al. (2010) calculations were 71.4 Mg C ha^{-1} and 101.8 Mg C ha^{-1} respectively at depth of 1 m. Larger values were obtained in Germany (114 Mg C ha^{-1}) and Central Europe (118 Mg C ha^{-1}) by Neufeldt (2005) and Batjes (2002). On the other hand, values of SOCCs for Cambisols lie between those proposed by Arrouays et al. (2001) ranging from 30 Mg C ha^{-1} for "permanent crops" and 121 Mg C ha^{-1} for Moors and Heathlands. Moreover, Batjes (2006) found similar estimations in Jordan for Cambisols, with values of 23 Mg C ha^{-1} at 0.3 m depth and 45 Mg C ha^{-1} at 1 m depth.

Soil organic C content for Regosols in this study is larger than values reported by other authors in Spain and other Mediterranean regions. Rodriguez- Murillo estimated 48.7 Mg C ha^{-1} and Díaz-Hernandez (2003) obtained 35 Mg C ha^{-1} at 0.5 cm depth and 52 Mg C ha^{-1} at 1 m depth and in Jordan, Batjes (2006) reported 8 Mg C ha^{-1}. Comparing to France, SOCCs of Regosols under "forest" are similar, around 50 Mg C ha^{-1} (Arrouays et al., 2001) but we estimated larger values under "permanent crops". We found similar SOCCs in Luvisols and Fluvisols, although larger values for Fluvisols were encountered under agricultural uses opposite to Luvisols which presented higher SOCCs under "forest" and "scrub". The highest values among all soil groups and land use types in this study were those obtained for Fluvisols under "maritime wetlands" (107.64 Mg C ha^{-1}) at 1m depth. Fluvisols are fertile soils and frequently occur under rice crops in wetlands. Most of the area covered by Luvisols, which have a great potential for a large number of crops when drainage is adequate, is under "permanent crops" and "arable land". Rodriguez -Murillo (2001) reported higher values for both Fluvisols and Luvisols in Spain, 75.8 Mg C ha^{-1} and 66 Mg C ha^{-1} respectively, nonetheless our estimations are within the values propose in France (Arrouays et al., 2001). They estimated SOCCs ranging from 27 Mg C ha^{-1} under permanent crops to 102 Mg C ha^{-1} under pastures for Fluvisols, and 29 Mg C ha^{-1} Mg C ha^{-1} under permanent crops to 84 Mg C ha^{-1} under pastures.

Planosols and Solonchaks occupy 1916.20 and 1481.70 km^2 respectively, mostly under "arable land". Planosols are frequently used for grazing, nevertheless, under specific management they can be used for cultivation. Solonchaks are widespread in the arid and semi-arid climatic zones and land uses are limited by the salt content. Thus, in the study area low values are found under “arable land” and relatively large under “maritime wetlands” (15.85 Mg C ha^{-1} and 70.80 Mg C ha^{-1} respectively). These results are in agreement with those estimated in Spain by Rodriguez-Murillo (2001), with 76.3 Mg C ha^{-1}. Generally, SOC contents are larger in the surface layer declining with depth. This is in agreement with previous studies (e.g.: Batjes, 1996; Salome et al., 2010). In arid soils from SE Spain, for example, Albadalejo et al. (2011) found that SOC from different soil types showed significant variations within the first 30 cm, and suggested that these variations were caused mainly by land use and precipitation. Nevertheless, the distribution of SOC with depth is likely to vary with different soil types (Schrumpf et al., 2008). More than 50% of the organic C of all studied soil groups was stored in subsoil horizons (0-25 cm), the layer more susceptible to change upon land use change especially agricultural and forest management. These results are in line with Schöning et al. (2006) and Grüneberg et al. (2010). In particular Leptosols, which are commonly shallow soils with limited soil development, accumulate 83.9% in the first 0.25 m (with 97.4% of the SOC content in the first 0.5 m). Most of the Leptosols are under “scrub and/or herbaceous associations” and “forest”, and SOCCs obtained in this research for Leptosols were lower than values reported by other areas in similar regions (Rodriguez- Murillo, 2001; Batjes, 2006).Soil organic carbon under “forest” is below other land uses with similar areas, as “arable land” or “permanent crops”. This may be explained as a consequence of the low degree of development of forest soils, where Cambisols, Leptosols and Regosols are dominant. Leptosols under “forest”, for example, occupy an area 6.9 and 3.2 times larger than under “arable land” and “permanent crops”, respectively.

4.4.2 Relationship between SOCC and environmental variables

It is crucial to determine the different factors explaining SOC stocks at different scales (Dai and Huang, 2006; Rodeghiero et al., 2010). According to Jenny (1941), climate is the main factor that influences the soil organic matter content through its effect on inputs (related to biomass production) and outputs produced by the microbial metabolism (influenced in turn by the climate and water availability). Natural or anthropic processes favouring increased biomass production (such as soil fertility, photosynthetic efficiency, fertilization, etc.) should be favourable to the decrease in atmospheric C content, by fixation in biomass or in soil (Macías et al., 2004).

The correlation between SOC content and winter temperature was positive for most soil groups, although significant correlation coefficients were only observed for Cambisols and Luvisols. Correlation coefficients between SOC content and summer temperature were mostly negative, but significant correlations were only observed for Fluvisols. Other authors have reported negative correlations between temperature and SOC content (Hontoria et al., 1999; Ganuza and Almendros 2003; Dai and Huang, 2006). Concentrations of organic C are usually higher in cold environments, where decomposition rates are low (Paustian, 2002). However, the range of temperatures in the studied area is not as wide as those observed in broad scale studies (e.g.: Dai and Huang, 2006), and local processes can be significant. Our results suggest that extremely low winter and extremely high summer mean temperatures in the study area contribute to a decrease in SOC content. Significant correlation coefficients were observed for precipitation and SOC content from “forest” ($r = 0.7908$) and “heterogeneous agricultural areas” ($r = -0.7454$), but contradictory results exist and a clear trend was not observed. Weak and no significant correlation was found when all soil profiles were considered. This is in contrast with results from other authors in Spain (Hontoria et al., 1999; Rodriguez-Murillo, 2001). Hontoria et al. (1999) obtained $r = 0.55$ for the whole country and Ganuza and Almendros (2003) estimated $r = 0.5675$ in the Basque Country (North Spain). Jobággy and Jackson (2000) analysed a large amount of soil profiles in the United States and elsewhere reporting values of $r = 0.5$ for 1 m depth. In a recent research, Ruiz Sinoga et al. (2012) have found that SOC sequestration in Mediterranean rangelands from southern Spain is reduced one order of magnitude from soil profiles under humid (59,9 Mg ha^{-1}) to semiarid (11.6 Mg ha^{-1}) climatic conditions. High and significant negative correlations were observed between SOC content and elevation for Vertisols. Also, high (but non-significant) correlations were observed for Cambisols ($r = -0.8775$) and Fluvisols ($r = -0.7219$). Other soils showed weak and non-significant correlations. For LU types, elevation was significantly correlated to SOC content only in “heterogeneous agricultural areas”. When all groups were considered, weak and no significant correlations were observed between SOC and elevation, in contrast with other studies by Hontoria et al. (1999) and Rodriguez-Murillo (2001), although these authors considered soil data from the Iberian Peninsula.

4.4.3 Limitations of the methodology

It is known that soil properties have a high spatial variability and, according to many authors, organic C is one of the soil parameters with highest variability (Don et al., 2009; Hontoria et al., 1999; Schrumpf et al., 2008). We found relatively high CV among groups, particularly large in natural land uses such as “forest” and “scrub”, which is in accordance with many authors. Batjes (2006) obtained CVs over 150% for some soil groups in Central Europe and even larger values in his study of the total C in the soils of the world (Batjes, 1996). In Spain, for example, Rodriguez-Murillo (2001) reported CVs between 49.3 and 136.0% for SOC concentrations under the main land use types. Relatively high CV are usual for regional or national scale studies and the IPCC assume that there are uncertainties on absolute stock values calculations and therefore high quality data sets should be used to reduce estimation uncertainty. It is necessary to assume some uncertainty when using average values with high CV in small scale studies (as in national or regional inventories).

Soil groups are not homogenously distributed. Cambisols, Fluvisols, Leptosols, Luvisols, Regosols, and Vertisols account for 93.29% of the study area, whereas Arenosols, Calcisols, Planosols and Solonchaks correspond to 6.71%. Consequently, when these soils are subdivided per LU class, the number of soil profiles per soil-LU combination is sometimes low. However, these combinations are representative of small areas which do not alter significantly global estimations.

Many empirical models have been proposed for explaining the relationship between SOC content and climatic factors. Global data show that organic C content increases in soils under high rainfall and low temperature (Oades, 1988). At detailed scales, anthropic transformation of ecosystems may strongly affect SOC content. Intensification of agricultural management, silviculture or afforestation, for example, may buffer the impact of climate on SOC. As a consequence, regional or local-scale studies may not show strong dependence between SOC content and climatic variables. Also, in the context of global change, other SOC redistribution or sequestration processes might be considered, as the increasing frequency of wildfires. At wide scale, wildfires are assumed to increase the organic C stock in soils, as reported by González-Pérez et al. (2004). At local scale, redistribution processes of soil organic matter by water erosion processes following wildfires may be substantial. It has been reported that erosion and the subsequent deposition after forest fires constitute a sink for C-rich sediments at the valley bottoms. In addition, C losses by soil erosion at the hillslopes may be replaced by the production of new biomass (Novara et al., 2011)

4.5 Conclusions

This study comprises the first comprehensive analysis of current organic C stocks for each soil group under present land use types in Andalusia, S Spain. In this research soil organic C pools and their distribution within the soil profile, are estimated under existing land uses, providing baseline information to assess the potential of the different soil groups for SOC sequestration. Soil organic C stocks are estimated at different depths (0-25, 25-50 and 50-75 cm) under different land use/soil associations. Cambisols and Regosols are the most common soil groups in Andalusia, but Calcisols and Vertisols show the highest SOCC values, above 65 Mg C ha^{-1}. In total, SOC stock is 415 Tg in the upper 75 cm and on average, with 55% stored in the first layer (0-25 cm). The amount of SOC in the first 75 cm was significantly correlated with annual mean temperature, annual mean precipitation and elevation in natural areas. Regional studies for assessing soil organic C stocks are needed and should include information about LU/LC and soil type. Nevertheless, large uncertainties in estimates of SOC stock prevail. These uncertainties can be also attributed to gaps in our understanding of both future land C content and quantification of the response of C sequestration according to land use change. Therefore, the role of future land use change in C stocks is considered in further research.

CHAPTER 5

CARBOSOIL MODEL: A LAND EVALUATION TOOL TO ASSESS SOIL ORGANIC CARBON SEQUESTRATION CAPACITY

5.1 Introduction

Under the Kyoto Protocol (1997) to the United Nations Framework Convention on Climate Change (1992), national governments are required to assess and report national atmospheric carbon emissions and removals reflected as changes in C pools. Thus, carbon stocks and changes in terrestrial C pools need to be quantified accurately at regional and global scales (Johnson and Kern, 2002). Many countries are currently using the Intergovernmental Panel on Climate Change (IPCC) guidelines for greenhouse gas inventories that provide a default methodology for soil C accounting. However, soil sampling processes and chemical analysis to assess and report SOC stock changes involve high costs (Jandl et al., 2011). Thus, several countries are currently using existing soil C simulation models or developing new methods for that purpose (Lokupitiya and Paustian, 2006).

Models are effective tools for assessing SOC stocks and dynamics at different scales (Kutsch et al., 2009) and predict C sequestration trends under projected scenarios (Álvaro-Fuentes and Paustian, 2011; Ju et al., 2007). In addition to C reporting and assessment studies, models are also increasingly being used as decision support tools, in particular on issues related to land use or climate change (e.g. Smith et al., 2005). Decision support systems (DSSs) are informatics structures that combine data and knowledge from different sources. These computational tools help in the organization and analysis of information, making possible the evaluation of underlying hypotheses (Eom et al., 1998; Janssen et al, 2005; Sauter, 1997; Wang et al., 2010). Empirical models based on regression/correlation techniques are not able to explain complex mechanisms within the soil system. However, they are useful tools to identify different drivers of SOC dynamics and perform projections of SOC stocks (Viaud et al., 2010). Although a number of studies have developed models for soil depth up to 1 metre, such as Roth-C (Coleman and Jenkinson, 1995, 1996) or Yasso (Liski et al. 2005), most of the research on modelling SOC dynamics have focused on the upper layer without specification of the vertical distribution such as CENTURY model (Parton et al., 1988) or EPIC (Izaurralde et al., 2006). Several works have proved that the deeper layers in the soil profile stores a considerable amount of C, which had previously not been considered into global C estimates (Batjes, 1996; Jobbagy and Jackson, 2000; Tarnocai et al., 2009).

The main objective of this research is to develop a basic model (CarboSOIL) for predicting SOC stocks and changes in Mediterranean areas under different scenarios of climate and land use and soil management practices, at different soil depths. In order to achieve this goal, the specific objectives are: (1) to test different methodologies to build a simple and reliable model for soil carbon assessment (2) to validate the model in a different area than that used for calibration (3) to perform a sensitivity analysis to test the model and (4) to develop a computer based tool in a Geographical Information System (GIS) environment for spatial analysis of the inputs/outputs of the model.

CarboSOIL will be incorporated in the land evaluation decision support system MicroLEIS DSS (Anaya-Romero et al, 2011; De la Rosa et al., 2004) which was designed to assist decision makers to face specific agro-ecological problems. MicroLEIS DSS consists of interactive software and explanatory material useful to researchers, farmers, technicians and policy-makers interested in the sustainable use and management of soils, with special reference to the Mediterranean region. This system consists of three interactive databases for information storage climate, soils, and soil management, and 12 agro-ecological assessment models.

5.2 Material and Methods

5.2.1 Data input and pre-processing

Twenty two variables were extracted from several databases, covering topography, climate, land use and physical and chemical soil properties (Table 5.1). These variables were selected because of their availability and their potential relation with soil organic carbon.

Soil data were obtained from 1756 geo-referenced soil profiles located in Andalusia and Valencia region from the database of the Andalusian Regional Ministry of Environment (Jordán and Zavala, 2009) and the SEISnet soil database[1]. In order to homogenize information from soil profiles, soil variables were re-coded and imported to the geo-referenced SDBm Plus Multilingual Soil Profile Database, which contains a large amount of descriptive and analytical data fields (De la Rosa et al., 2002). Soil profiles showed a range of depths, therefore soil data (Table 5.1) were homogenized and re-sampled to standard soil depths for computing (0-75, 0-25, 25-50 and 50-75 cm). The SDBm Plus incorporates a “control section” function, to determine the thickness of the layer to be analysed within the soil profile. This function allows calculating the weighted average value for each variable in standard control sections. For each soil layer of the 1756 soil profiles, soil organic carbon content (SOCC) was estimated as follows:

$$\mathrm{SOCC} = \mathrm{SOC} \times \mathrm{BD} \times \mathrm{D} \times (1\text{-}\mathrm{G}) \qquad (1)$$

where SOCC is soil organic carbon or soil organic carbon content (Mg ha^{-1}), SOC is soil organic carbon percentage (g 100^{-1} g^{-1}), BD is bulk density (g cm^{-3}), D is the thickness of the studied layer (cm) and G is the proportion in volume of coarse fragments.

---

[1] http://www.evenor-tech.com/banco/seisnet/seisnet.htm

Table 5.1. Variables collected to be included as predictors in the model for training (Andalusia) and test (Valencia region).

Variable type				**Source and reference**	
	Variable name	**Code**	**Unit**	**Andalusia region**	**Valencia Region**
Dependent variable	Soil Organic C	SOCC	Mg/ha	Sdbm Plus database (2002) and other SDB (2009)	Sdbm Plus database (De la Rosa, 2002)
Climate	Total precipitation	PRPT	mm	REDIAM- CLIMA (2012) www.rediam.es	State Meteorological Agency (AEMET; 2012) www.aemet.es
	Winter Temperature	TDJF	^{o}C		
	Summer Temperature	TJJA	^{o}C		
Site	Elevation	ELEV	m	Digital Elevation Model of Andalusia (ICA, 1999)	
	Slope	SLOP	%		
	Drainage	DRAI	-	Sdbm Plus database (De la Rosa, 2002) and other SDB (Jordán and Zavala, 2009)	Sdbm Plus database (De la Rosa, 2002)
	Soil Erosion	SERO	-		
	Parent material	PMAT			
Soil	Nitrogen	NITRO	g/100g		
	pH	PHWA	-		
	Cation Exchange Capacity	CEXC	meq/100g		
	Sand	SAND	g/100g		
	Clay	CLAY	g/100g		
	Silt	SILT	g/100g		
	Bulk density	BULK	g/cc		
	Soil structure	STRU	-		
	Porosity	PORO			
	Electrical Conductivity	COND	mS/cm		
	Base saturation	BSAT	%		
	Field capacity	FCAP	g/100g	Simanctel Project (Monge et al, 2008)	
Land use	Land use/land cover	LULC	CLC LEVEL 3	Land use and land cover Map of Andalusia (2007)	SIOSE project (2005) www.siose.es

Climate data were obtained from the time series of the CLIMA subsystem of the Environmental Information Network of Andalusia (REDIAM, Andalusian Regional Government) which integrates numerous databases from a set of over 2200 observatories since 1971. Elevation and slope data were extracted from the 100 m resolution digital elevation model of Andalusia (ICA, 1999) derived from the topographic map of Andalusia (S 1:10,000).

Land use classification and land cover data for CarboSOIL were obtained from the Land Use and Land Cover Map of Andalusia (LULCMA) for 2007 at scale 1:25,000 and minimum map unit 0.5 ha (Moreira, 2007). This digital spatial dataset is a result of the Coordination of Information on the Environment (CORINE) program, promoted by the European Commission in 1985 for the assessment of environmental quality in Europe. The LULCMA provides an updated version of the original maps at scale 1:100,000 and constitutes thematically and geometrically detailed and accurate databases. Land cover classes of LULCMA were reclassified into Corine Land Cover (CLC) nomenclature at level 3, which contains 44 classes (Muñoz-Rojas et al., 2011). Agricultural areas, natural and semi-natural areas and wetlands were selected composing a total of 14 land cover classes (15 classes considering “other uses”).

The original dataset was integrated by training data (1698 soil profiles from Andalusia) and test data (58 soil profiles of Valencia region), in total 1756 soil sample points. From the total list of the variables previously selected, the following inputs were excluded for further analysis: parent material, structure, porosity, electric conductivity and base saturation. These variables were not considered in the model development because missing values were above 200. From the original dataset, cases with missing values in any variable were also excluded. The total of valid cases for modeling was composed for 1504 soil profiles for training (Andalusia) and 45 soil profiles for test (Valencia region).

5.2.2 Model selection and evaluation

Machine learning techniques, including decision trees, logistic regression (MLR), support vector machines (SVM) and artificial neural networks (ANN), have proved to be effective in potential distribution modelling (Lorena et al., 2011). To develop a new tool for prediction of potential SOC contents, SVM and ANN were applied to the complete dataset, obtaining accurate predictions. Table 5.2 shows the calculated correlation coefficient between the observed and the predicted values in the training and test dataset. However, interpretation of results from these methods is difficult due to their “black-box” nature, which makes them difficult to incorporate into a computer system without and additional module or library for interpretation.

Table 5.2. Statistical parameters obtained applying Support Vector Machine (SVM) and Artificial Neural Network (ANN) techniques.

Model	Training data			Test data		
	r^2	MSE	S-W test	r^2	MSE	S-W test
SVM	0.8978	259.9968	W= 0.6498. $p < 2.2\ 10^{-16}$	0.8393	331.9153	W= 0.8454. $p < 2.2\ 10^{-16}$
NNET	0.8238	410.1954	W= 0.8601. $p < 2.2\ 10^{-16}$	0.8245	357.4202	W= 0.9411. $p < 1.15\ 10^{-10}$

Regression techniques have been widely applied in environmental modeling due to the few predictors needed to explain the highest variability in the response variable. This modeling technique has several advantages, such as ease in application and simplicity of interpretation (Hastie et al., 2001; Oliveira et al., 2012). Random forest is a nonparametric technique derived from classification and regression trees, broadly used in ecological and soil modeling (Thompson et al., 2006; Grimm et al., 2008). Thus, Multiple Linear Regression (MLR) and Random Forest (RF) techniques were selected for the analysis, and their ability for modeling SOC stocks were tested. Both methods (MLR and RF) were built with the variables selected in previous steps and applied to the complete datasets using the SPSS and R Statistical Software (R Development Core Team, 2010). In order to obtain a normal distribution in the residuals, as required by the MLR model, different transformations were performed. A Box-Cox power transformation is a useful data pre-processing technique used to stabilize variance, make the data more normal distribution-like and improve the correlation between variables (Box and Cox, 1964). Accordingly, this transformation was considered in order to obtain a better prediction in MLR.

Among input variables, “Drainage” (DRAI), “Soil erosion” (SERO) and “Land use/land cover” (LULC) cannot be entered directly into a regression model and be meaningfully interpreted because they are categorical predictor variables. These categorical variables with n classes were transformed (or re-coded) into n-1 independent variables which takes the value “0” or “1”. This process is known as dummy coding and it is considered the simplest method of coding a categorical variable (Pedhazur, 1997). The variable DRAI with 3 classes (adequate, poor and excessive) was dummy coded into two dichotomous variables (poor and excessive). A soil profile with drainage classified as one of these was re-coded as “1” in the dataset. A soil profile with “0” is classified as adequate. The same procedure was performed for SERO (from 4 classes to 3 variables) and LULC (from 15 classes to 14 variables). All the classes of the categorical variables are described in the Appendix section.

5.2.3 CARBOSOIL as a GIS-tool

CarboSOIL model has been developed as a computer application to be implemented in MicroLEIS DSS. Each submodel of CarboSOIL was built as a spatial tool by using the Model Builder application and Visual Basic for Application of ArcGIS v.10 (ESRI, 2011), allowing users to perform spatial analysis and to obtain output SOC content maps under different scenarios.

5.3 Results

5.3.1 Model performance and validation

Table 5.3 and Figure 5.1 summarize the statistical parameters obtained for both training and testing datasets by using MLR, MLR with Box-Cox transformation and RF in each soil section. Observed values were compared to predicted values for each submodel.

Table 5.3. Statistical parameters for each submodel applying Multiple Linear Regression, Multiple Linear Regression with Box-Cox transformation (MLR-BC) and Random Forest (RF). MSE (Mean Square Error); S-W test: Shapiro-Wilk normality test.

Model	Training			Test		
	r^2	MSE	S-W test	r^2	MSE	S-W test
0-25						
MLR	0.9437	44.2680	W= 0.7140. $p < 2.2\ 10^{-16}$	0.9325	105.0321	W= 0.6721 $p= 7.98\ 10^{-8}$
MLR-BC	0.9689	25.1751	W= 0.7365. $p < 2.2\ 10^{-16}$	0.9560	50.2396	W= 0.7696 $p= 3.36\ 10^{-6}$
RF	0.9590	39.5388	W= 0.9407. $p < 2.2\ 10^{-16}$	0.9517	68.2356	W= 0.9469 p= 0.07693
25-50						
MLR	0.9547	16.8318	W= 0.6483. $p < 2.2\ 10^{-16}$	0.9664	52.4006	W= 0.581 $p= 8.181\ 10^{-9}$
MLR-BC	0.9800	7.5525	W= 0.6407. $p < 2.2\ 10^{-16}$	0.9860	13.4454	W= 0.6792 $p= 1.799\ 10^{-7}$
RF	0.8970	45.8382	W= 0.8590. $p < 2.2\ 10^{-16}$	0.9616	60.1119	W= 0.8874 p= 0.001841
50-75						
MLR	0.9686	6.7545	W= 0.5965. $p < 2.2\ 10^{-16}$	0.9906	4.0031	W= 0.8558 p= 0.003466
MLR-BC	0.9849	3.2658	W= 0.6292. $p < 2.2\ 10^{-16}$	0.9961	2.6207	W= 0.7089 $p= 1.828\ 10^{-5}$
RF	0.7821	51.6951	W= 0.7913. $p < 2.2\ 10^{-16}$	0.7985	80.5188	W= 0.8137 p= 0.0006394
0-75						
MLR	0.6628	760.4797	W= 0.9323. $p< 2.2\ 10^{-16}$	0.8538	499.5594	W= 0.9518 p= 0.1105
MLR-BC	0.4518	1752.2280	W= 0.6758 $p< 2.2\ 10^{-16}$	0.7662	4982.3340	W= 0.6481 $p= 3.551\ 10^{-8}$
RF	0.7237	636.8101	W= 0.8611 $p< 2.2\ 10^{-16}$	0.7021	1363.2630	W= 0.6481 $p= 3.551\ 10^{-9}$

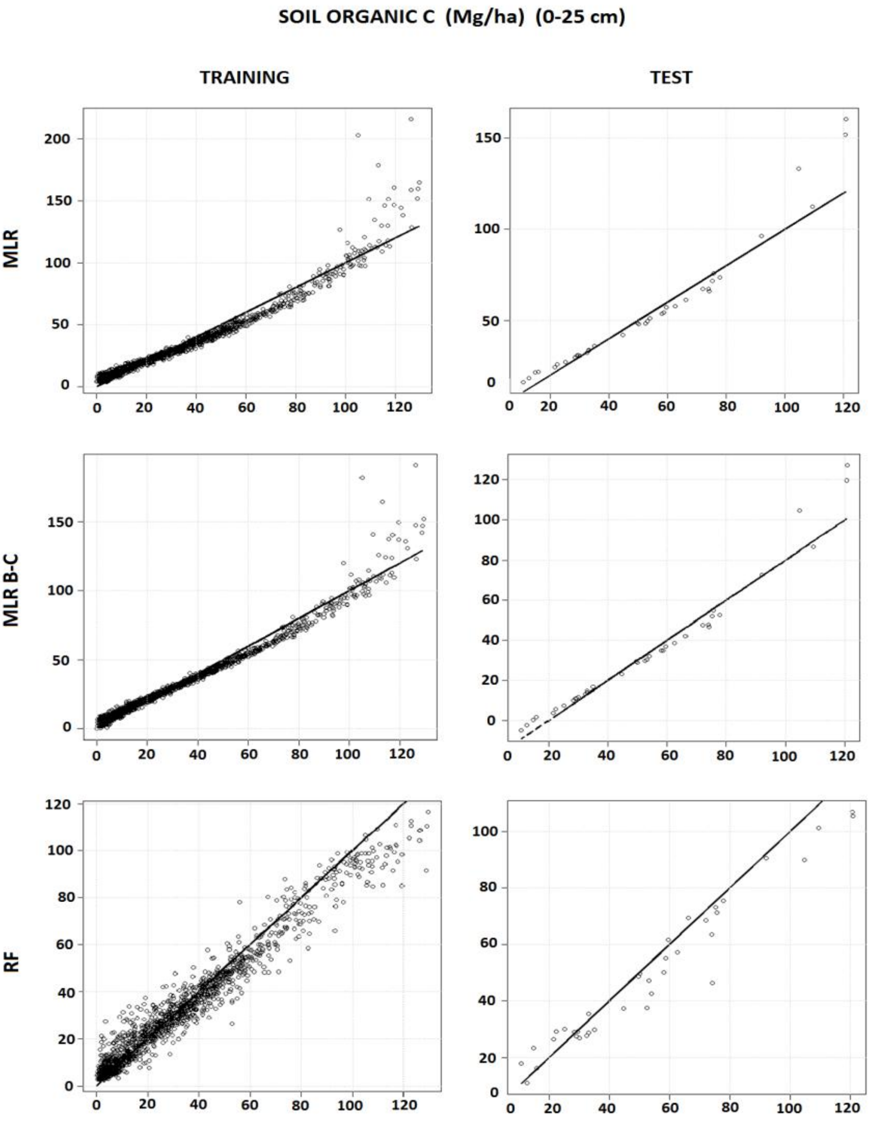


Figure 5.1a. Statistical parameters for Multiple Linear regression (MLR), Multiple Linear regression with Box-Cox Transformation (MLR-BC) and Random Forest (RF). Training and test datasets (0-25 cm). Observed values in horizontal axis and predicted values in vertical axis.

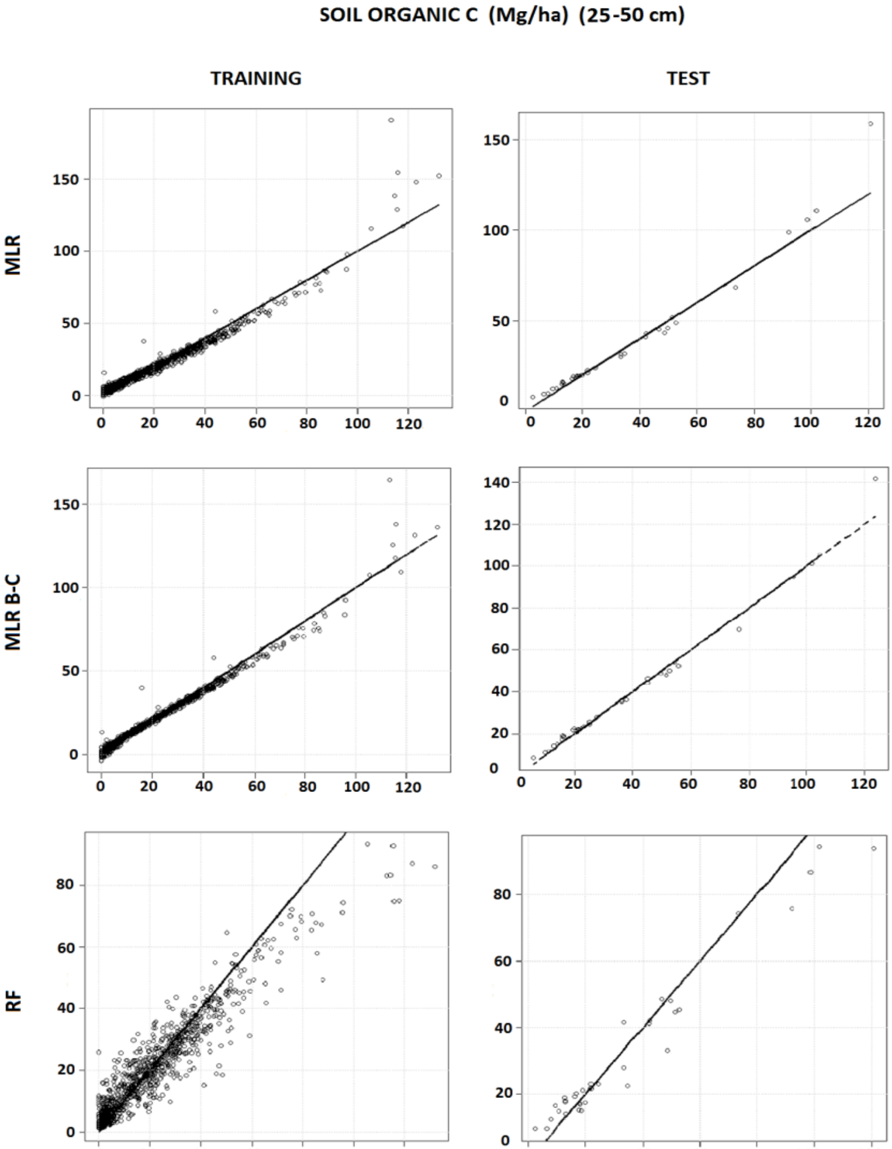


Figure 5.1b. Statistical parameters for Multiple Linear regression (MLR), Multiple Linear regression with Box-Cox Transformation (MLR-BC) and Random Forest (RF). Training and test datasets (25-50 cm). Observed values in horizontal axis and predicted values in vertical axis.

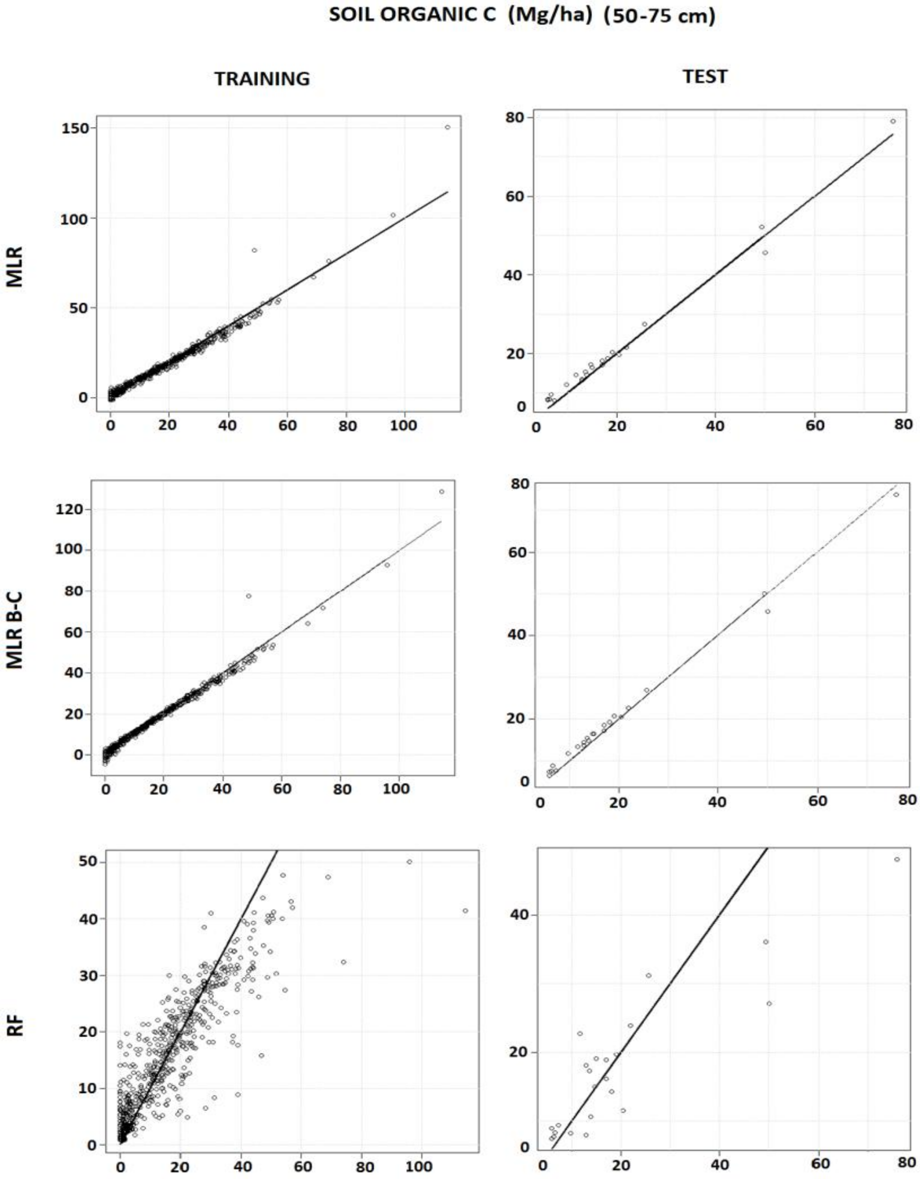


Figure 5.1c. Statistical parameters for Multiple Linear regression (MLR), Multiple Linear regression with Box-Cox Transformation (MLR-BC) and Random Forest (RF). Training and test datasets (50-75 cm). Observed values in horizontal axis and predicted values in vertical axis.

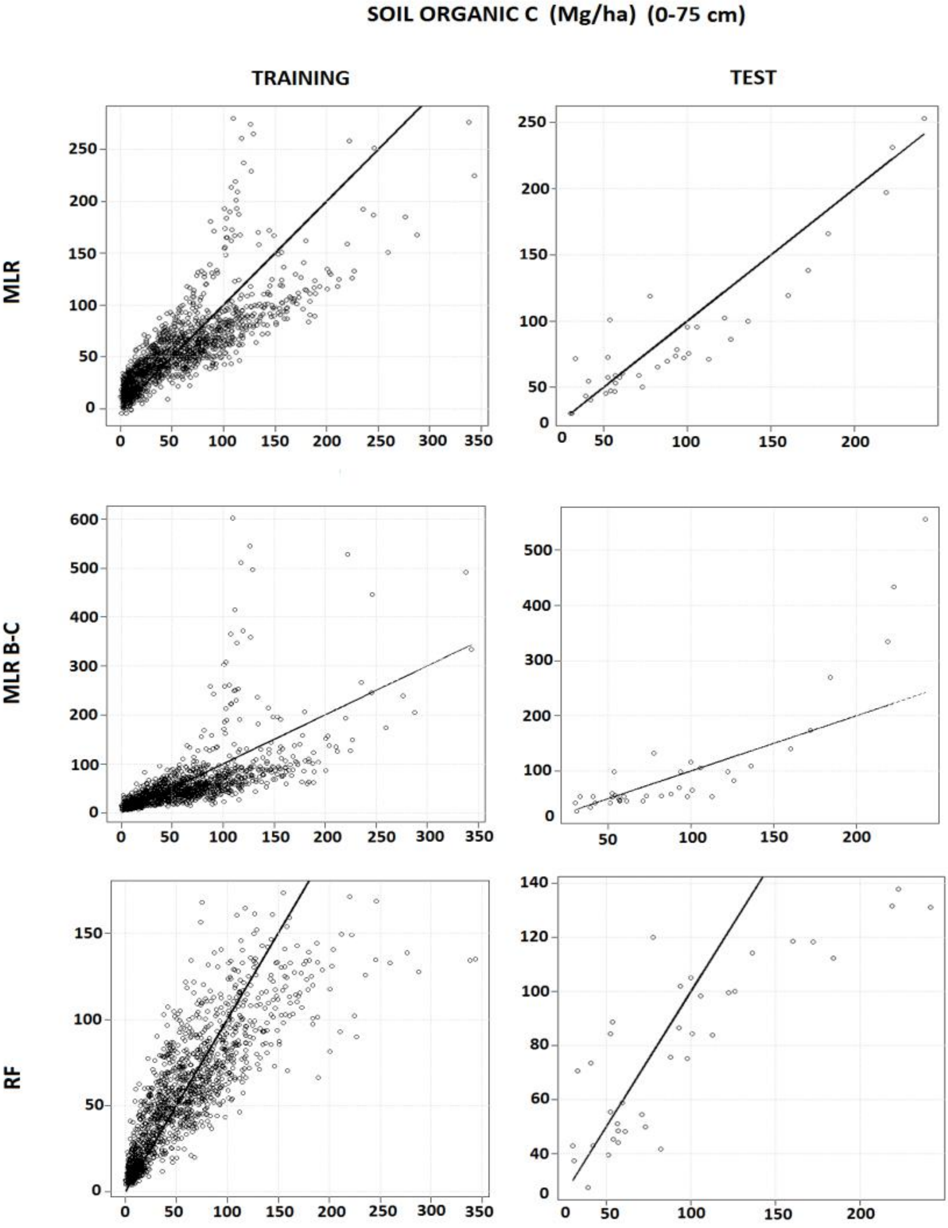


Figure 5.1d. Statistical parameters for Multiple Linear regression (MLR), Multiple Linear regression with Box-Cox Transformation (MLR-BC) and Random Forest (RF). Training and test datasets (0-75 cm). Observed values in horizontal axis and predicted values in vertical axis.

The MLR model showed a higher predictive ability than RF in the section 0-75 cm. In the different subsections (0-25, 25-50 and 50-75 cm), the MLR with Box-Cox transformation obtained better predictions. For each submodel, coefficients obtained were r^2= 0.9689 and mean square error (MSE) = 25.1751 in the training set and r^2= 0.9650, MSE 50.2396 in the test set for the 0-25 cm layer; r^2= 0.9800 and MSE 7.5525 in the training set and r^2 = 0.9860, MSE = 13.4454 in the test set for the 25-50 cm layer; and r^2= 0.9849 and MSE = 3.2658 in the training set and r^2 = 0.9961, MSE = 2.6207 in the test set for the 50-75 cm layer. For the complete soil profile (0-75 cm) the best prediction was obtained with MLR. The percentage of variance explained with this model was 66.28% in the training and 85.38% in the test (r^2= 0.6628 and MSE = 760.4797 in the training set and r^2= 0.8538, MSE = 499.5594 in the test set).

5.3.2 Model structure

The final model was built with the predictor variable and the 15 independent variables selected, applying MLR in the total soil profile (0-75 cm) and MLR with Box-Cox transformation in the subsections 0-25, 25-50 and 50-75 cm. The list of variables with statistical parameters is shown in Table 5.4. The supplementary Figure S5.1 shows the relation between input factors, soil processes and outputs. In order to validate the model, confident intervals were applied to each coefficient by bootstrapping. Bootstrapping is a method for assigning measures of accuracy to sample estimates. This statistical technique allows estimation of the sampling distribution of almost any statistic using very simple methods. Significance of coefficients can be evaluated by determining whether their 95% confidence limits, extracted from bootstrap analysis, overlapped zero. The bootstrap intervals include zero when the estimated regression coefficient is non-significant and exclude zero when the estimated coefficient is significant. The model was run again using only the highly significant variables selected by bootstrapping, but poorer predictions were obtained.

5.3.3 Sensitivity analysis

To assess the causal relationship between soil conditions and land use on the one hand and SOC dynamics on the other hand, the sensitivity of SOC dynamics was analyzed with CarboSOIL model. Sensitivity of the model for organic nitrogen content, pH, cation exchange capacity, clay content, elevation and slope was tested for each land use by varying these factors between the ranges of their values, whereas the rest of variables are set with their average values (Table 5.5).The results of the sensitivity analysis are shown in Figure 5.2. The model has proved to be sensitive in all land uses for the following variables related to soil chemical properties: organic nitrogen content and pH. In the sensitivity analysis for site variables analysis major responses were obtained for elevation and slope.

Table 5.4. Coefficients and confidence intervals (95%) of model variable for each submodel.

	CarboSOIL 25			**Carbosoil50**			**Carbosoil75**			**Carbosoil TOTAL**		
	Coef	**BCainf**	**BCasup**	**Coef**	**BCainf**	**BCasup**	**Coef**	**BCainf**	**BCasup**	**Coef**	**BCainf**	**BCasup**
Interc.	774.69	745.17	802.13	1085.65	1059.45	1111.74	1150.92	1120.70	1172.05	546.54	482.75	608.97
Climate												
PRPT	0.00	-0.01	0.00	0.00	-0.01	0.01	0.00	-0.01	0.00	0.02	0.00	0.03
TDJF	1.43	0.38	2.56	0.62	-0.29	1.53	0.64	-0.11	1.40	3.52	1.36	5.73
TJJA	-0.93	-1.74	-0.09	-0.69	-1.39	0.09	0.07	-0.49	0.77	-1.91	-3.59	-0.31
Site												
ELEV	0.00	-0.01	0.01	0.00	-0.01	0.00	0.00	0.00	0.01	0.00	-0.02	0.01
SLOP	0.00	-0.03	0.02	0.00	-0.01	0.01	0.00	-0.01	0.01	0.01	-0.03	0.04
DRAI												
ad	-	-	-	-	-	-	-	-	-	-	-	-
df	-2.08	-3.65	-0.34	-1.50	-2.90	-0.21	-0.21	-1.34	0.87	-4.60	-8.25	-1.13
ex	1.89	-1.05	4.04	-2.39	-6.00	-0.56	-4.08	-8.24	-2.34	-10.48	-15.36	-5.16
SERO												
ne	-	-	-	-	-	-	-	-	-	-	-	-
se	-1.00	-3.02	0.95	-0.88	-2.50	0.69	-0.40	-1.83	0.84	-0.44	-4.91	3.74
re	-0.16	-2.22	2.01	0.45	-1.32	2.32	-0.47	-1.82	0.85	-2.05	-6.85	2.33
ge	-0.33	-2.85	2.25	1.22	-1.77	3.27	-0.88	-3.62	0.75	-8.45	-14.03	-3.07
Soil												
NITRO	1.93	-9.64	10.39	26.31	15.04	34.54	6.06	-0.56	12.20	-4.57	-28.71	21.65
PHWA	0.84	0.05	1.63	0.07	-0.48	0.72	1.04	0.55	1.61	2.30	0.74	3.99
CEXC	-0.01	-0.05	0.02	0.00	-0.04	0.03	0.03	-0.02	0.07	0.06	-0.03	0.15
SAND	0.80	0.76	0.85	1.06	1.02	1.10	1.16	1.13	1.20	0.49	0.39	0.58
CLAY	-1.19	-1.26	-1.13	-1.60	-1.65	-1.54	-1.69	-1.73	-1.64	-0.54	-0.67	-0.41
BULK	-493.9	-501.1	-486.0	-686.5	-693.8	-676.6	-746.99	-755.15	-734.38	-348.9	-368.9	-330.7
FCAP	0.02	-0.11	0.15	-0.07	-0.16	0.04	0.00	-0.09	0.09	0.03	-0.24	0.30
Land use												
LULC												
ot	-	-	-	-	-	-	-	-	-	-	-	-
nr	1.17	-2.19	8.46	-0.53	-3.42	5.59	-0.47	-2.65	4.75	1.41	-8.03	11.38
pr	-1.48	-5.46	5.26	0.86	-2.27	7.28	-0.58	-2.98	4.42	8.48	-1.80	18.74
vn	-0.21	-10.16	6.99	-3.23	-9.86	2.22	-1.82	-6.55	2.58	7.61	-8.40	24.86
fr	-1.01	-8.66	5.87	-0.52	-6.96	4.55	1.07	-2.82	6.35	-5.73	-20.34	7.88
ol	1.48	-2.08	8.41	-0.23	-3.45	5.99	-0.31	-2.58	4.67	3.56	-6.29	13.60
cm	-0.37	-5.09	6.50	-1.07	-5.61	4.26	-2.22	-5.39	2.65	0.68	-10.53	11.95
af	-0.05	-3.96	7.00	-1.63	-4.86	4.83	-0.06	-2.42	5.37	-2.50	-13.07	7.87
bf	-0.34	-4.17	6.88	-2.41	-5.57	3.77	0.03	-2.36	5.55	-5.24	-15.17	5.53
cf	0.28	-3.96	7.50	-1.37	-5.50	4.39	0.70	-2.37	6.07	0.05	-11.16	11.09
mf	6.33	-2.57	13.22	-1.38	-8.98	4.38	0.98	-2.65	6.40	-2.40	-17.71	14.02
gr	1.51	-2.85	8.27	0.41	-3.93	5.90	-0.53	-3.84	5.09	-0.94	-11.81	10.34
sc	1.36	-2.83	8.22	-0.64	-4.56	5.23	-2.02	-5.10	3.00	-1.97	-12.59	9.02
wd	1.40	-2.63	8.54	-3.40	-7.22	2.41	1.33	-1.54	6.85	-2.08	-12.88	8.65
sm	-2.46	-14.11	4.62	-3.06	-10.86	3.74	-3.58	-7.25	2.13	-26.04	-43.47	-8.01

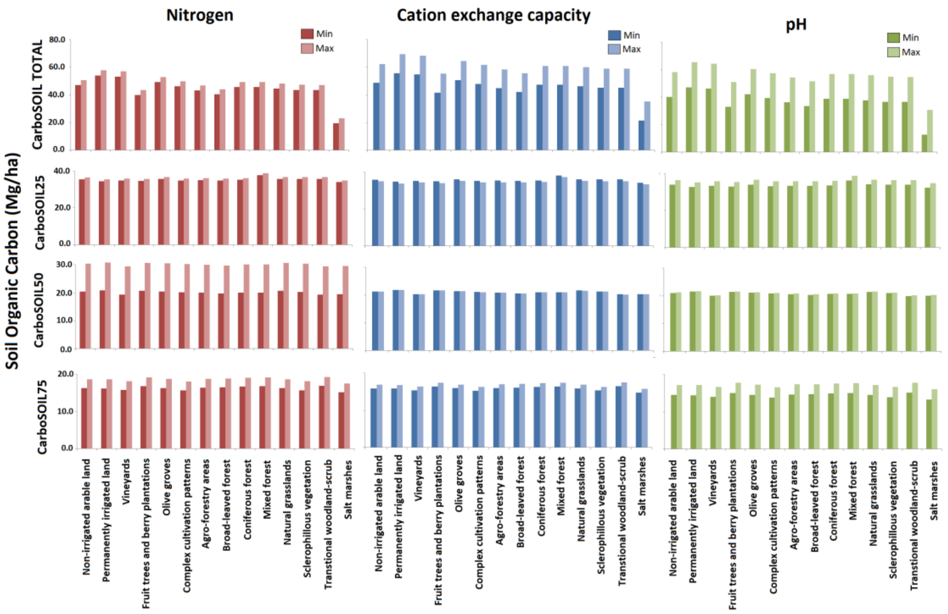


Figure 5.2a. Sensitivity analysis of CarboSOIL model for soil factors (nitrogen, cation Exchange capacity and pH.

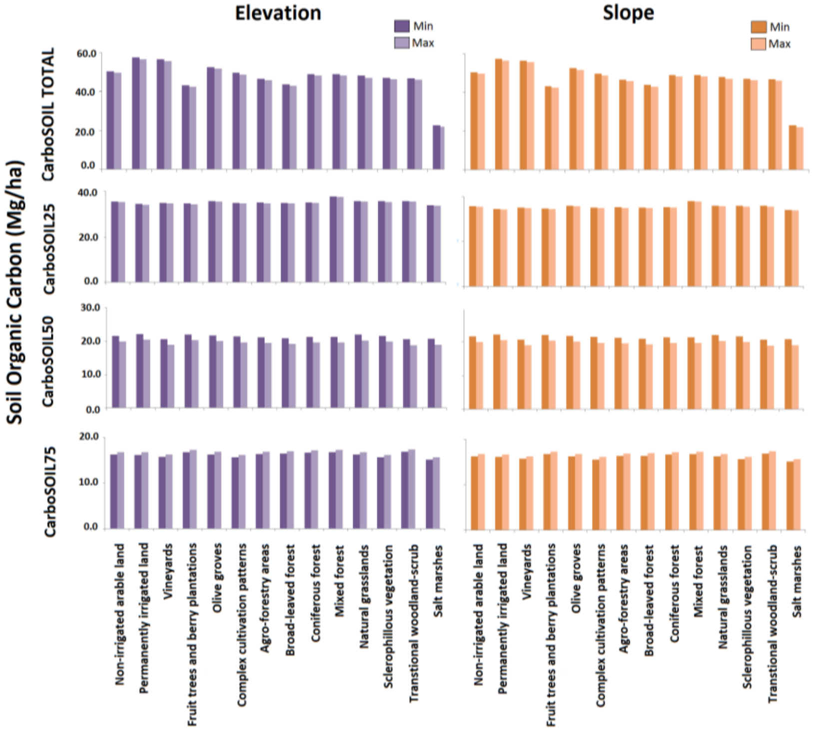


Figure 5.2b. Sensitivity analysis of CarboSOIL model for site factors (elevation and slope).

Table 5.5. Statistical parameters of CarboSOIL variables for sensisitivity analysis.

		CarboSOIL TOTAL				**CarbosSOIL25**				**CarboSOIL50**				**CarboSOIL75**			
Variable	**Code**	**Min**	**Max**	**Mean**	**CV**	**Min**	**Max**	**Mean**	**CV**	**Min**	**Max**	**Mean**	**CV**	**Min**	**Max**	**Mean**	**CV**
Dependent variable																	
Soil Organic C (Mg/ha)	SOC	0.0	343.0	51,4	92,4%	0,0	130	30,4	91,6%	0,0	131,9	19,0	100,8%	0,0	114,4	14,90	98,2%
Site																	
Elevation (m)	ELEV	1.0	1352,0	341,7	77,2%	1,0	1352	342	77,2%	1,0	1352,0	334,4	75,8%	1,0	1199,0	322,70	76,4%
Slope (%)	SLOP	0.0	100,0	11,6	132,8%	0,0	100	11,6	132,8%	0,0	100,0	10,0	142,3%	0,0	100,0	8,50	144,5%
Soil																	
Nitrogen (g/100 g)	NITRO	0.0	0,8	0,1	100,0%	0,0	1,1	0,1	94,5%	0,0	1,1	0,1	103,2%	0,0	1,1	0,10	120,2%
pH	PHWA	2.1	10,0	6,5	18,5%	2,1	8,9	6,6	17,7%	1,0	17,2	6,6	20,2%	1,8	8,9	6,70	19,8%
Cation Exchange Capacity (meq/100g)	CEXC	0.1	244,5	16,4	103,0%	0,1	229	16,5	103,7%	0,0	232,6	16,8	99,6%	0,0	97,6	16,90	75,1%
Clay (g/100g)	CLAY	0.0	87,6	22,1	71,0%	0,0	87,6	20,8	73,8%	0,0	80,0	24,0	71,6%	0,0	82,2	26,40	69,3%

5.3.4 ARCGIS tool

Figure 5.3 shows the interface of CarboSOIL tool. CarboSOIL submodels (CarboSOIL25, CarboSOIL50, CarboSOIL75 and CarboSOIL TOTAL) run independently as script tools in the Arc Toolbox environment within the ArcGIS 10 software.

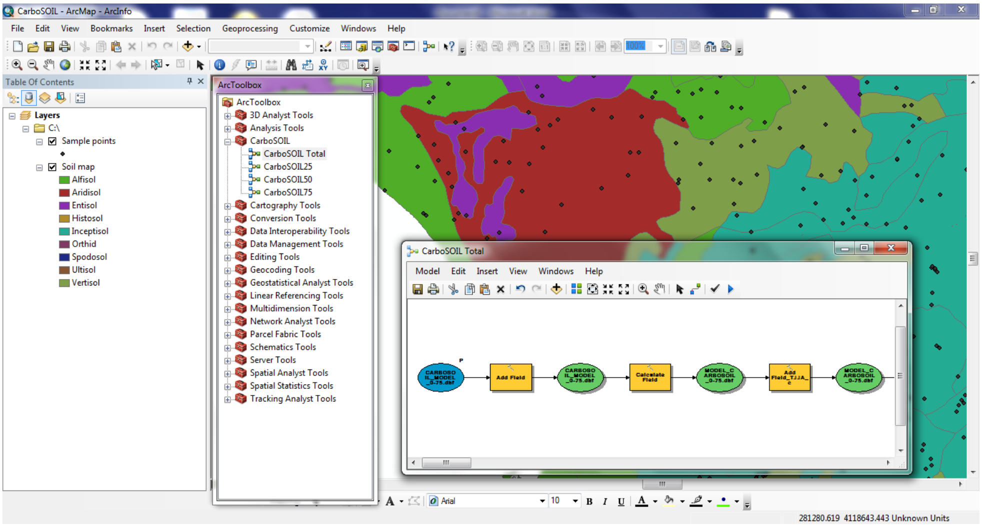


Figure 5.3. Interface of CarboSOIL model tool in ArcGIS 10.

5.4 Summary and conclusions

In this study different methodologies have been tested to design a new tool to predict SOC stocks in different scenarios of soil management, land use and climate change at different soil depths. Higher predictions have been obtained with MLR techniques and Box-Cox transformation procedures. The model has been trained in Andalusia and tested in Valencia, both typically Mediterranean areas. CarboSOIL model is divided in four submodels (CarboSOIL25, CarboSOIL50, CarboSOIL75 and CarboSOIL TOTAL) which predict SOC contents at different soil depths (0-25 cm, 25-50 cm, 50-75 cm and 0-75 cm).

This model has been developed as a computer application to be implemented in MicroLEIS DSS, and each submodel has been built as a spatial tool in a GIS environment for spatial analysis of the inputs/outputs of the model. CarboSOIL is a useful tool to accurately quantify and understand the distribution of soil carbon.

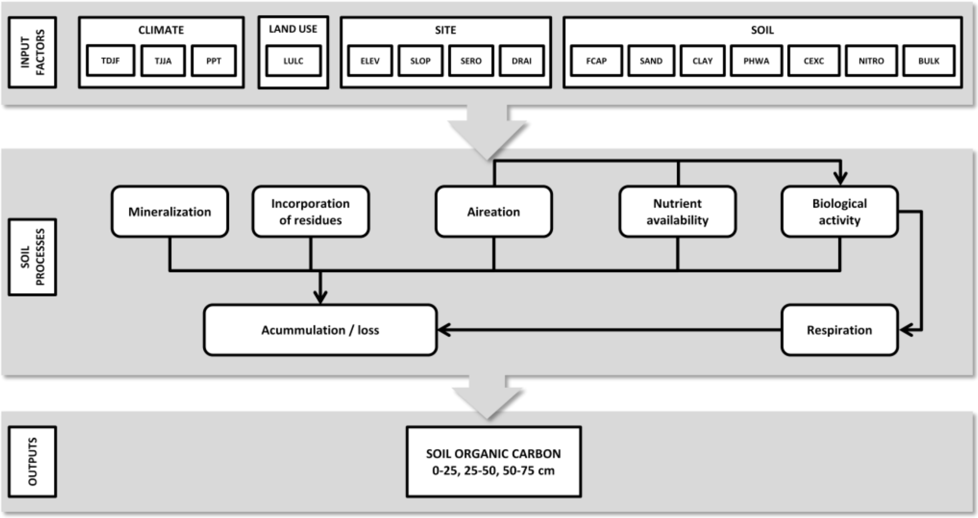


Figure S51.General diagram of CarboSOIL model: input factors, soil processes and outputs. Soil factor abbreviations as in Table 5.1.

CHAPTER 6

MODELLING SOIL ORGANIC CARBON STOCKS IN CLIMATE CHANGE SCENARIOS: A CARBOSOIL APPLICATION

6.1 Introduction

Global climate is changing as a consequence of the increasing levels of atmospheric CO_2 concentration and global mean temperatures (IPCC 2007). Soil organic C is strongly influenced by climate conditions and SOC stocks are determined by the balance between the total amount of C released to the atmosphere in the form of CO_2, and the total amount withdrawn from the atmosphere as net C inputs to the soil (Janssens et al., 2005). Carbon stored in soils is the largest C pool in most terrestrial ecosystems holding around 1,500 Pg C in the top metre, approximately twice the amount of carbon in the atmosphere and in vegetation (Lal, 2004). Thus, small changes in the SOC pool could have a great impact on atmospheric CO_2 concentrations. Only a difference of 10% in SOC would equal the total anthropogenic CO_2 emissions of the last 30 years (Kirschbaum, 2000). Global warming and climate change, as a result of anthropogenic CO_2 emissions, may significantly affect both SOC storage and soil capacity for C sequestration. Increases in soil temperature and atmospheric CO_2 have been related to higher decomposition rates and changes in net primary productivity (NPP). Increased temperatures might enhance the release of CO_2 to the atmosphere from SOC, leading to higher CO_2 levels and accelerated global warming (Davidson and Janssens, 2006). On the other hand, soil carbon sequestration, considered as the net removal of CO_2 from the atmosphere, could help to alleviate the problem of global warming and climate change. Carbon sequestration in terrestrial ecosystems is one of the most important ecosystem services due to its role in climate regulation (IPCC, 2007).

At the same time, soil C sequestration provides important benefits for soils, crops and environment quality associated with increasing levels of SOC carbon such as improved soil structure, soil fertility, water holding capacity, infiltration capacity, water use efficiency and soil biological health (which results in higher nutrient cycling and availability). Additionally, soil organic C prevents from soil erosion and desertification and enhances bio-diversity. Soil carbon accumulation capacity should be considered regarding to adaptation strategies to climate change, in view of the high resilience of soils with an adequate level of organic C to a warming, drying climate (Christensen et al., 2011). The potential effects of climate change on SOC dynamics are still largely uncertain (Álvaro-Fuentes and Paustian, 2011; Zaehle et al., 2007). In order to formulate adaptation policies in response to climate change impacts, it is crucial to assess soil carbon stocks and evaluate their dynamics in future climate scenarios (Chiesi et al., 2010). Different approaches have been used to assess the impact of global warming and climate change on SOC stocks. Several studies have estimated regional and global soil organic C stocks based on extrapolations from measured data to future climate scenarios (Eswaran et al., 1993; Smith et al., 2000). The major drawback of these methods is the assumption of a constant rate of SOC change over the time period. Models are effective tools to assess C stocks and C dynamics (Falloon et al., 2002; Falloon and Smith, 2003; Jones et al., 2005; Paustian et al., 1997), what makes them appropriate for C reporting and assessment studies. They are particularly useful as decision support tools (DSSs) on climate change issues (Smith et al., 2005). DSSs combine data and knowledge from different sources to help in the organization and analysis of information, making thereby possible the evaluation of underlying hypotheses (Janssen et al., 2005; Sauter, 1997; Wang et al., 2010).

Modelling allow us to predict the short, medium and long-term trends of SOC dynamics and SOC sequestration under projected future scenarios of climate change (Lucht et al., 2006; Smith et al., 2005; Wan et al., 2011). By linking simulation models to spatial datasets (soils, land use), it is possible to determine current and future estimates of regional SOC stocks and SOC sequestration (Batjes, 2006; Falloon et al., 1998; Hashimoto et al., 2012). Moreover, patterns in SOC dynamics related to soil and land use features can be analyzed. Scenario-driven impact assessments require detailed spatial and temporal data on the projected future climate. Several Global Climate Models (GCMs) have been developed, providing adequate simulations of atmospheric general circulation at the continental scale and projecting precipitation, temperature, and other climate variables (Mitchel et al., 2004). GCMs require information on future GHG emissions generated by socio-economic scenarios and models. The IPCC SRES (Special Report on Emissions Scenarios - SRES) make available estimates of future anthropogenic CO2 emission. These scenarios contain various driving forces of climate change and are widely used to assess potential climate changes (Christensen et al., 2011).

Some of the current available SOC models simulate SOC dynamics only in the topsoil (upper 20-30 cm) (Parton et al., 1987) whereas others are specific for certain agricultural management conditions (Coleman and Jenkinson, 1999). There is evidence that in deeper soil layers a considerable amount of carbon can be stored. In addition, this form of C has proven to be more stable (Jobbagy and Jackson, 2000). Therefore, models should consider vertical SOC distribution in order to improve SOC stocks predictions. Climate change will affect SOC stocks differently under diverse land uses and soil types. Each soil type show different properties and consequently different vulnerability to climate conditions and C sequestration capacity. Consequently there is a need to predict the potential SOC stocks in different soil types and under different land uses (Christensen et al., 2011).

In this study we use CarboSOIL model together with climate outputs from different GCMs (BCCR-BCM2, CNRMCM3, and ECHAM5) driven by SRES scenarios (A2, A1B and B2) to study the effects of climate change on SOC dynamics in a Mediterranean region (Andalusia, S Spain). The main objectives are: (a) to test and validate CarboSOIL model in climate change scenarios in different time periods, (b) to perform a sensitivity analysis of

CarboSOIL for climate variables, c) to estimate SOC contents in future climate projections for different land uses and soil types, (d) to obtain spatial distribution and SOC stocks for different climate projections.

6.2 Materials and methods

6.2.1 CarboSOIL model application

CarboSOIL is a land evaluation tool for soil carbon accounting under different scenarios (Anaya-Romero et al., 2012). This model was developed as part of a global project for developing a land evaluation tool for assessment of soil C sequestration capacity, as a new component of the MicroLEIS Decision Support System (Anaya- Romero et al., 2011; De la Rosa et al., 2004;). CarboSOIL was designed to simulate soil C dynamics of natural or cultivated systems under different scenarios. The model is divided in 4 modules or sub models which predict soil organic carbon contents at different depths: a) CarboSOIL25 (0-25 cm), b) CarboSOIL50 (25-50 cm), c) CarboSOIL75 (50-75 cm) and d) CarboSOIL TOTAL (0-75 cm). The input variables to run the model are divided in I) climate variables (mean winter/summer temperature and annual precipitation), II) site variables (elevation, slope, erosion, type-of-drainage), III) soil (pH, N, cation exchange capacity, sand/clay content, bulk density and field capacity), and IV) land use (Table 6.1).

CarboSOIL model has been applied to 1356 plots covering a range of soil types, land uses, site and climate conditions throughout the study area. The model has been designed as a GIS tool. Thus, although CarboSOIL is applied at plot-scale, output data can be linked to spatial datasets to perform spatial analysis and quantify SOC stocks.

6.2.2 Climate data and scenarios

CarboSOIL requires the following climate parameters to run: annual precipitation (mm), mean winter temperature (average of December, January and February monthly temperature, ^{o}C) and mean summer temperature (average of June, July and August monthly temperature, ^{o}C). Climate data for baseline and future climate change scenarios were obtained from the time series of the CLIMA subsystem of the Environmental Information Network of Andalusia (REDIAM[1]) which integrates several databases from a set of over 2200 observatories since 1971. These data include climate spatial datasets in raster format for different SRES emissions scenarios, obtained by statistical downscaling of different GCMs. The downscaling techniques are based on inverse distance interpolation and regression modelling of regional/local physiographic features.

---

[1] http://www.juntadeandalucia.es/medioambiente/site/web/rediam

Table 6.1. CarboSOIL model input variables, units and sources.

Variable type	Variable name	Code	Unit	Source and reference
Dependent variable	Soil Organic C	SOC	Mg/ha	Jordán y Zavala (2009) and SDBm Plus database (2002)
Climate	Total precipitation	PRPT	mm	REDIAM- CLIMA http://www.juntadeandalucia.es/medioambiente/site/web/rediam
	Winter Temperature	TDJF	°C	
	Summer Temperature	TJJA	°C	
Site	Elevation	ELEV	m	Digital Elevation Model of Andalusia, 100 m (ICA, 1999)
	Slope	SLOP	%	
	Drainage	DRAI		
	Soil Erosion	SERO		Jordán and Zavala (2009) and SDBm Plus database (2002)
Soil	Nitrogen	NITRO	g/100g	
	pH	PHWA		
	Cation Exchange Capacity	CEXC	meq/100g	
	Sand	SAND	g/100g	
	Clay	CLAY	g/100g	
	Bulk density	BULK	g/cc	
	Field capacity	FCAP	g/100g	
Land use	Land use/land cover	LULC		Land use and land cover Map of Andalusia (2007)

Three GCMs were selected for the application of CarboSOIL, a) BCCR-BCM2 (Bjerknes Centre for Climate Research, Norway), b) CNRMCM3 (Centre National de Recherches Meteorologiques, Meteo France) and c) ECHAM5 (Max Planck Institute for Meteorology, Germany). These three GCMs represent a spread of model characteristics and thus their scenario climates (Mitchell et al., 2004). For each GCM, we obtained monthly temperature and annual precipitation under three different CO_2 emissions scenarios (B1, A1B, A2; Table 6.2) as defined in the IPPC Report, 4th Assessment in Emissions scenarios (SRES; Nakicenovic et al., 2000; IPPC, 2007). We selected climate series for four periods: 1961-2000 (baseline climate period), 2011-2040 (2040, the “near-future” period), 2041-2070 (the “mid-future” period) and 2071-2100 (the “far-future” period). Data was extracted by using ArcGIS Spatial Analyst extension tool (ESRI, 2011) and analyses were performed with SPSS software (SPSS, 2009).

6.2.3 Site data

Elevation and slope data were extracted from the 100 m resolution digital elevation model (DEM) of Andalusia (ICA, 1999). This DEM is derived from the topographic map of Andalusia (S 1:10,000). Type of fluvial network (drainage) and active soil erosion processes (sheet erosion, rill erosion and gully erosion) were obtained from 1356 soil profiles reported and described by Jordán and Zavala (2009) and the SEISnet soil databases.

Table 6.2. Summary of the IPPC Fourth Assessment climate change scenarios used for simulation during the 2000-2100 period.

Scenario	Temperature change (°C)		Main characteristics
	Best estimate	Likely Range	
A1B	2.8 °C	1.7 - 4.4 °C	Low population growth, very high GDP growth, very high energy use, low-medium land use changes, medium resource (mainly oil and gas) availability, rapid pace and direction of technological change favouring balanced development.
A2	3.4	2.0 - 5.4	High population growth, medium GDP growth, high energy use, medium-high land use changes, low resource (mainly oil and gas) availability, slow pace and direction of technological change favouring regional economic development.
B1	1.8 °C	1.1 - 2.9 °C	Low population growth, high GDP growth, low energy use, high land use changes, low resource (mainly oil and gas) availability, medium pace and direction of technological change favouring efficiency and dematerialization.

These geo-databases consist of descriptive and analytical data, including site attributes, horizon description, chemical and physical analysis.

6.2.4 Soil data

Soil data were derived from the 1356 soil profiles reported and described by Jordán and Zavala (2009) and the SEISnet soil databases. Selection of soil profiles was carried out considering homogeneous sampling and analysis methods. Soil variables used in this study were soil depth (cm), nitrogen (g/100g), pH, cation exchange capacity (meq/100 g), sand (%), clay (%), bulk density (g/cc), field capacity (g/100g) and organic carbon (%). In order to homogenize information from soil profiles, soil variables were re-coded and imported to the geo-referenced SDBm Plus Multilingual Soil Profile Database, which contains a large amount of descriptive and analytical data fields (De la Rosa et al., 2002). Soil profiles showed a range of depths, therefore soil data (Table 6.1) were homogenized and re-sampled to standard soil depths for computing (0-75, 0-25, 25-50 and 50-75 cm). The SDBM Plus database incorporates a “control section” function, which allows determining the thickness of the layer to be analyzed within the soil profile. This function calculates the weighted average value for each variable in standard control sections. For each soil layer of the 1356 soil profiles, soil organic carbon content (SOCC) was estimated as follows:

$$SOCC = SOC \times BD \times D \times (1\text{-}G) \qquad (1)$$

where SOCD is soil organic carbon content (Mg ha^{-1}), SOC is soil organic carbon percentage (g 100^{-1} g^{-1}), BD is bulk density (g cm^{-3}), D is the thickness of the studied layer (cm) and G is the proportion in volume of coarse fragments. Soil profiles were classified following original soil profile descriptions into 10 reference groups (IUSS Working Group WRB, 2006): Arenosols, Calcisols, Cambisols, Fluvisols, Leptosols, Luvisols, Planosols, Regosols, Solonchaks and Vertisols.

6.2.5 Land use and land cover data

Land use for the model application was obtained from the Land Use and Land Cover Map of Andalusia (LULCMA) for 2007 at scale 1:25,000 and minimum map unit 0.5 ha (Moreira, 2007). This digital spatial dataset, obtained after the analysis of satellite images (Landsat TM, IRS/PAN and SPOT-5) and digital aerial photographs, is a result of the Coordination of Information on the Environment (CORINE) programme, promoted by the European Commission in 1985 for the assessment of environmental quality in Europe. Within the CORINE programme, CORINE Land Cover (CLC) project provides consistent information on land cover and land cover changes across Europe. The LULCMA for 2007 provides an updated version of the original maps at scale 1:100,000 and constitutes a more detailed and accurate database, both thematically and geometrically.

The standard CLC nomenclature includes 44 land cover classes, grouped in a three-level hierarchy. Land cover classes of LULCMA were reclassified into CLC nomenclature at level 3 (the most detailed level) according to the method described in Muñoz-Rojas et al. (2011), in order to apply CARBOSOIL model. Agricultural areas, natural and semi-natural areas and wetlands were selected composing a total of 14 land cover classes (“non irrigated arable land”, “permanently irrigated land”, “vineyards”, “fruit trees and berry plantations”, “olive groves”, “complex cultivation patterns”, “agro-forestry areas”, “broad-leaved forests”, “coniferous forests”, “mixed forests”, “natural grasslands”, “sclerophyllous vegetation”, “transitional woodland-scrub and salt marshes”).

6.2.6 Simulation process

For each plot, CarboSOIL model (CarboSOIL 25, CarboSOIL50, CarboSOIL75 and CarboSOILTOTAL) was run under the different climate change scenarios to obtain SOC contents for each soil profile at different soil depth. Data analyses were performed using ArcGIS v.10 software (ESRI, 2011) and SPSS (SPSS, 2009). Soil profiles were grouped into association of soil and land use units (landscape units). These landscape units are defined by one soil type, classified according to IUSS Working Group WRB (2006) (Arenosols, Calcisols, Cambisols, Fluvisols, Leptosols, Luvisols, Planosols, Regosols, Solonchaks and Vertisols) and one aggregated land cover type at level 2 of CLC nomenclature (“arable land”, “permanent crops”, “heterogeneous agricultural areas”, “forest”, “scrub and/or herbaceous vegetation associations”, “open spaces with little or no vegetation” and “maritime wetlands”).

To determine SOC stocks in present and future scenarios, the study area was divided into landscape units using a topological intersection of the LULCMA for 2007 and the Soil Map of Andalusia (CSIC-IARA, 1989) at scale 1:400,000. The overlay of both maps resulted in a new spatial dataset composed by 85,492 new polygons. Mean values of SOC contents

(Mg ha^{-1}) of each landscape unit for each climate change scenario were assigned to all the new polygons. SOC stocks were determined by multiplying SOC content mean values by the area occupied by the landscape unit in the overlay map.

6.2.7 Model validation and sensitivity analysis

Correlation between modelled baseline scenarios (current scenario) and measured SOC pools from soil databases were determined. The Kolmogorov-Smirnov test was used to test whether differences between observed and predicted SOC contents were significant. Analyses were performed with SPSS software for each submodel (CarboSOIL 25, CarboSOIL50, CarboSOIL75 and CarboSOILTOTAL).

A sensitivity analysis of SOC dynamics was carried out with CarboSOIL model to assess the causal relationship between climate and land use variables, and SOC dynamics on the other hand. Sensitivity of the model for annual precipitation, mean summer temperature and mean winter temperature was tested for each land use type. The model was applied modifying these climate variables (using minimum and maximum values, Table 6.3), whereas the rest of variables were set with their average values.

6.3 Results

6.3.1 Model performance and validation

Measured SOC contents were well correlated with the predicted values in baseline scenarios for each submodel with R Spearmen values ranging between 0.884 and 0.989 (Table 6.4). Model performance proved to be more accurate at the submodel level (CarboSOIL25, CarboSOIL50 and CarboSOIL75). Nevertheless, CarboSOIL TOTAL showed a satisfactory ability to predict SOC contents.

The results of the sensitivity analysis showed that the model was sensitive to climate parameters in all land uses (Figure 6.1). Predicted SOC contents were remarkably responsive to precipitation. Increases in annual precipitation enlarge SOC in the top layer and the total soil profile (submodels CarboSOIL TOTAL and CarboSOIL25), but decrease SOC in the deeper layers (submodels CarboSOIL50 and CarboSOIL75). Modelling under different temperature regimes shows that SOC increases when winter temperature increases in all the soil profile sections. The model was highly sensitive to summer temperatures. SOC contents decrease on increasing summer temperature in the total profile and the upper layers (up to 50 cm). However, it increases upon increasing summer temperature in the deeper layer (50-75 cm).

Table 6.3. Description of climate variables in the study area in projected climate change scenarios in different periods: 2040 (2011-2040), 2070 (2041-2070) and 2100 (2071-2100).

Climate change scenario	**TDJF (^{o}C)**				**TJJA(^{o}C)**				**PPT(mm)**			
	Baseline	**2040**	**2070**	**2100**	**Baseline**	**2040**	**2070**	**2100**	**Baseline**	**2040**	**2070**	**2100**
BCCR-BCM2 -A1B												
Low	4.6	4.9	5.8	6.3	19.7	19.5	21.0	21.9	357.0	308.0	290.0	282.0
High	13.5	13.6	14.3	14.8	27.1	26.9	28.3	29.4	2,304.0	1625.0	1376.0	1257.0
Mean	10.1	10.3	11.2	11.7	25.1	24.9	26.3	27.5	761.8	589.1	529.2	484.2
±SD	1.6	1.5	1.4	1.4	1.0	1.0	1.0	1.1	218.8	154.8	134.2	121.7
BCCR-BCM2 -A2												
Low	4.6	5.1	5.5	6.4	19.7	19.8	20.6	22.4	357.0	303.0	291.0	269.0
High	13.5	13.8	14.0	14.9	27.1	27.2	27.9	30.0	2,304.0	1571.0	1368.0	1199.0
Mean	10.1	10.4	10.8	11.8	25.1	25.2	26	28.1	761.8	577.1	510.1	470.7
±SD	1.6	1.5	1.4	1.4	1.0	1.0	1.0	1.1	218.8	149.4	132.8	117.5
BCCR-BCM2 - B1												
Low	4.6	5.2	5.1	5.7	19.7	20.0	20.4	20.9	357.0	311.0	293.0	295.0
High	13.5	13.9	13.5	14.1	27.1	27.4	27.9	28.4	2,304.0	1709.0	1380.0	1456.0
Mean	10.1	10.5	10.2	11.0	25.1	25.5	25.9	26.4	761.8	597	519.6	545.4
±SD	1.6	1.5	1.4	1.4	1.0	1.0	1.0	1.0	218.8	160.4	132.8	140.5
CNRMCM3- A1B												
Low	4.8	5.5	4.1	4.4	19.7	18.3	19.7	22.3	303.0	189.0	145.0	138.0
High	13.7	13.7	14.5	15.0	27.1	27.8	28.8	31.0	1,861.0	1,701.0	1,375.0	1,306.0
Mean	10.3	10.4	11.3	11.7±	25.2	25.9	27	28.9	614.5	624.4	539.6	511.9
±SD	1.6	1.2	1.4	1.4	1.0	1.0	1.1	1.2	178.2	167.8	137.7	131
CNRMCM3- A2												
Low	4.8	2.5	4.2	4.7	19.7	18.1	20.1	23.6	303.0	172.0	124.0	142.0
High	13.7	13.6	14.5	15.1	27.1	27.6	29.2	32.3	1,861.0	1645.0	1,338.0	1,301.0
Mean	10.3	10.3	11.3	11.9±	25.2	25.8	27.3	30	614.5	615.6	521.5	510.4
±SD	1.6	1.5	1.4	1.4	1.0	1.0	1.1	1.2	178.2	165	132.4	130
CNRMCM3- B1												
Low	4.8	2.9	3.0	3.8	19.7	18.6	19.4	19.3	303.0	164.0	170.0	144.0
High	13.7	13.9	13.9	14.3	27.1	28.0	28.7	28.5	1,861.0	1488.0	1544.0	1391.0
Mean	10.3	10.6	10.6	11.1±	25.2	26	26.7	26.6	614.5	572.3	586.4	542.1
±SD	1.6	1.5	1.5	1.4	1.0	1.0	1.1	1.0	178.2	150.7	154.3	140.1
ECHAM5- A1B												
Low	4.6	4.8	5.7	7.2	19.6	20.7	22.3	23.3	341.0	316.0	290.0	299.0
High	13.6	13.5	14.3	15.5	27.0	28.0	29.7	31.6	2,232.0	1,653.0	1,428.0	1,374.0
Mean	10.1	10.2	11.1	12.6±	25	26	27.7	29.4	738.2	602.9	534.3	536.8
±SD	1.6	1.5	1.5	1.4	1.0	1.0	1.1	1.3	210.1	158.8	138.1	137.7
ECHAM- A2												
Low	4.6	4.7	5.7	6.9	19.6	20.8	21.9	23.5	341.0	316.0	309.0	277.0
High	13.6	13.6	14.3	15.3	27.0	28.2	29.2	31.7	2,232.0	1,653.0	1,530.0	1,263.0
Mean	10.1	10.1	11.1	12.3	25	26.2	27.3	29.6	738.2	602.9	566.3	487.1
±SD	1.6	1.5	1.5	1.4	1.0	1.0	1.1	1.3	210.1	158.8	147.7	125.7
ECHAM- B1												
Low	4.6	5.1	5.5	6.0	19.6	20.6	21.3	22.9	341.0	318.0	309.0	307.0
High	13.6	13.7	14.0	14.6	27.0	27.8	28.4	30.0	2,232.0	1,662.0	1,582.0	1,469.0
Mean	10.1	10.3	10.7	11.3±	25	25.8	26.5	28.1	738.2	609.8	577.9	542
±SD	1.6	1.5	1.5	1.4	1.0	1.0	1.0	1.1	210.1	160.9	151.9	140.6

Table 6.4. Measured and modelled soil organic C (SOC) content (Mg/ha) under different climate scenarios (BCCR-BCM2, CNRMCM3 and ECHAM5) and results of the Kolmogorov-Smirnov test. (*) Correlation is significant at the 0.01 level.

Soil depth (cm)	N	R Spearman*	Measured SOC		BCCR-BCM2 Modelled SOC		CNRMCM3 Modelled SOC		ECHAM5 Modelled SOC		Kolmogorov-Smirnov test (p)
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	
0-25	1504	0.989	30.51	28.11	31.36	29.93	31.7	26.89	31.48	26.9	< 0.01
25-50	1033	0.990	19.66	19.18	19.82	18.60	19.88	18.60	19.87	18.59	< 0.01
50-75	600	0.992	15.65	14.67	15.87	14.31	15.92	14.31	15.88	14.31	< 0.01
0-75	1504	0.884	51.25	47.55	54.78	38.82	52.51	38.66	54.47	38.88	< 0.01

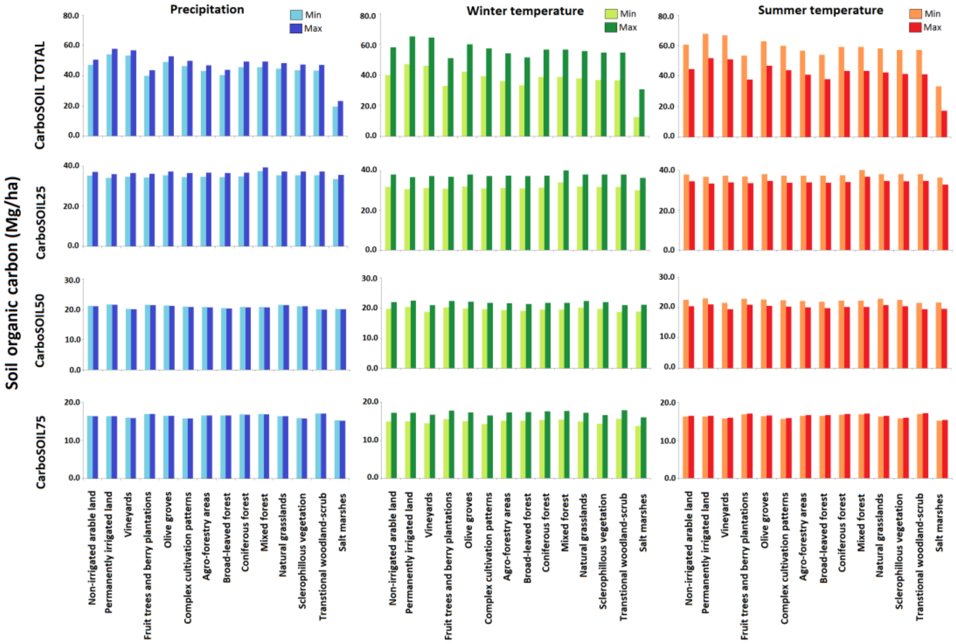


Figure 6.1. Sensitivity analysis of CarboSOIL model for climate variables (annual precipitation, mean winter temperature and mean summer temperature) at different soil depths: 0-25 (CARBOSOIL25), 25-50 (CARBOSOIL50), 50-75 (CARBOSOIL75) and 0-75 cm (CARBOSOIL TOTAL).

6.3.2 Prediction of SOC stocks and projected SOC changes in response to climate change

SOC stocks at different depth under different SRES scenarios and GCM models

Total SOC stocks predicted for 2040, 2070 and 2100 according to each SRES scenario and GCM are shown in Figure 6.2. In the upper 25 cm SOC stocks range between 228.5 and 234.5 Tg in 2040, 229.1 and 235.1 Tg in 2070 and 226.5 and 234.2 in 2100. In the soil section from 25-50 cm the SOC pool vary from 151.5 to 154.9 Tg in 2040, 149.9 to 153.5 Tg in 2070 and 146.7 to 153.3 Tg in 2100.

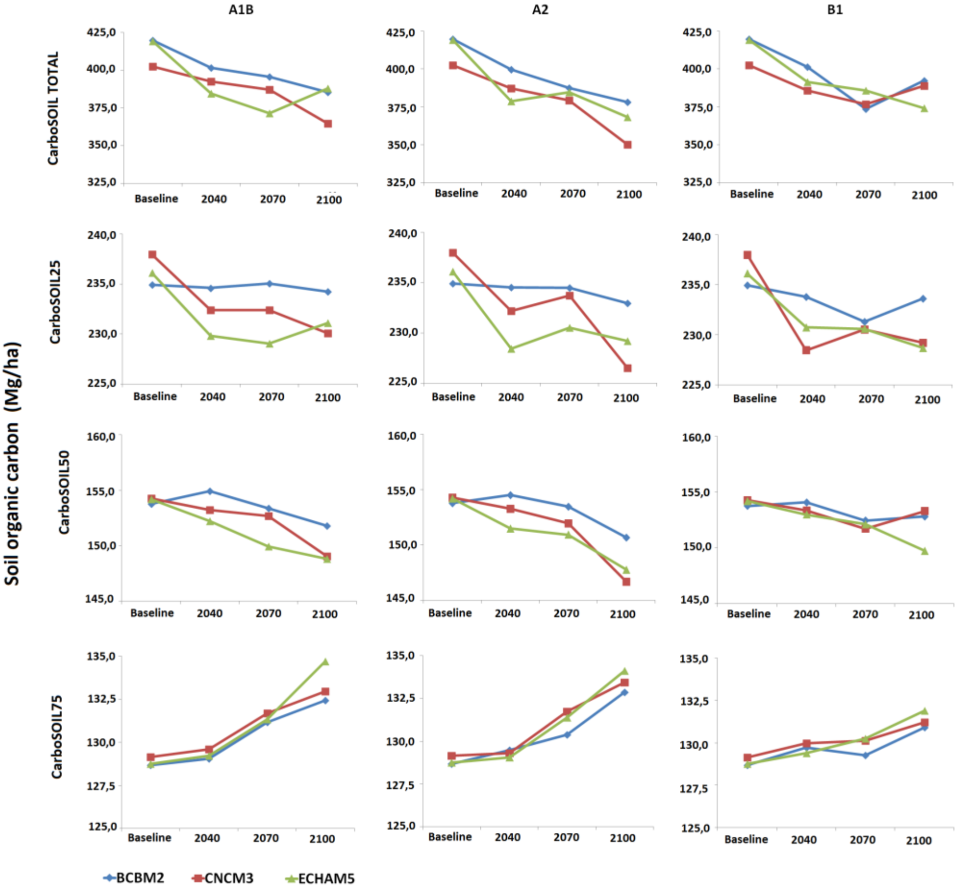


Figure 6.2. Soil organic C stocks in climate change scenarios for each GCM and SRES in different periods (2040, 2070 and 2100) at different soil depths 0-25 (CARBOSOIL25), 25-50 (CARBOSOIL50), 50-75 (CARBOSOIL75) and 0-75 cm (CARBOSOIL TOTAL).

SOC stocks in the deeper soil section studied (50-75 cm) ranged between 129.0 and 130.0 in 2040, 129.3 and 131.7 in 2070 and 130.9 and 134.7 in 2100. The projected SOC stocks in the total soil profile (0-75) vary from 378.7 to 401.7 in 2040, from 371.6 to 395.5 in 2070 and 350.2 to 392.3 in 2100.

Table 6.5 shows the simulated future percentage change of SOC stocks in the long-term scenario 2100 compared with its values in the baseline scenarios. Values are provided for each SRES scenario and GCM and SOC changes range from -3.4% to -13.0% in the 0-75 soil section. The CNRMCM3 GCM forced by A2 SRES scenario predicted larger decreases of SOC stocks in the upper 25 cm, the 25-50 cm layer and the total soil profile (0-75). In soil section from 50 to 75 cm, all scenario combinations showed increases of SOC stocks. ECHAM5 GCM forced by A1B SRES scenario projected the largest increment. Figure 6.3 displays the spatial distribution of changes in soil organic carbon content) for different SRES scenarios and different periods (2040, 2070 and 2100) in Andalusia.

Changes in SOC stocks in different soil types at different depth

The predicted change of SOC stocks in different soil reference groups and soil depths according to average GCMs scenarios is displayed in Figure 6.4. Although there is an overall trend in all soil groups towards decreasing of SOC stocks in the upper soil sections (0-25 and 25-50), predicted SOC stocks tend to increase in the deeper soil section (0-75) with future climate scenarios. In Calcisols, Fluvisols, Luvisols and Vertisols, larger depletion of SOC stocks occur in the upper 25 cm in all projected scenarios. In Arenosols, Cambisols and Leptosols, major SOC loses are found in the upper 25 cm in 2040 and 2070. However, in 2100 larger decreases are produced in the soil section from 25-50 cm. Generally, SOC stocks increase in projected climate change scenarios in the deeper soil section (50-75) but in Cambisols these rates are particularly large, accumulating 5.7% and 5.9% in A1B and A2 scenarios respectively.

Table 6.5. Changes in SOC stocks at different soil depths in different SRES (A1B, A2 and B1) and global climate models (BCCR-BCM2, CNRMCM3 and ECHAM5) in the period 2000-2100.

Soil section (cm)	A1B			A2			B1		
	BCCR-BCM2	CNRMCM3	ECHAM5	BCCR-BCM2	CNRMCM3	ECHAM5	BCCR-BCM2	CNRMCM3	ECHAM5
0-25	-0.3%	-3.3%	-2.1%	-0.9%	-4.8%	-2.9%	-0.6%	-3.7%	-3.1%
25-50	-1.3%	-3.4%	-3.5%	-2.0%	-4.9%	-4.2%	-0.6%	-0.6%	-2.9%
50-75	2.9%	2.9%	4.6%	3.2%	3.3%	4.2%	1.7%	1.6%	2.4%
0-75	-8.2%	-9.4%	-7.5%	-9.9%	-13.0%	-12.2%	-6.5%	-3.4%	-10.8%

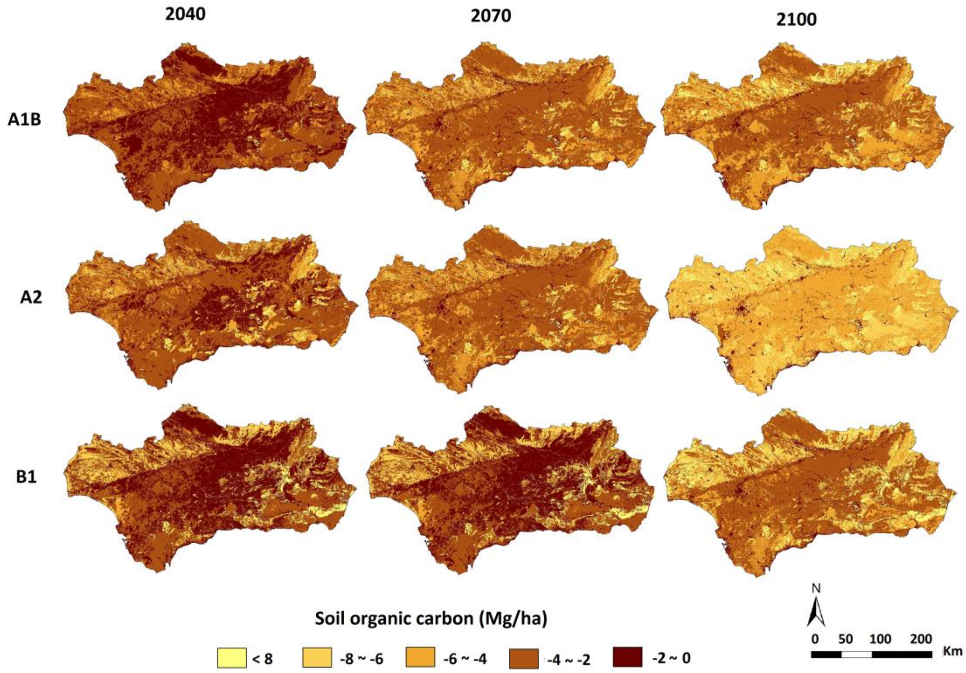


Figure 6.3. Spatial distribution of changes in soil organic carbon content (Mg/ha) in Andalusia (Southern Spain) for different SRES scenarios and different periods (2040, 2070, 2100).

Among all studied soil groups, Planosols are the most affected by climate change with the highest losses of SOC stocks. In particular, in the A2 scenario (years 2100 and 2070) the decreases reach 6.3 % and 5.7% of current SOC stocks in 0-25 cm and 25-50 cm respectively. Opposite to other soil groups, SOC stocks decline in the soil section between 50 and 75 cm of Planosols. In 2040, SOC losses are predicted in A1B and A2 scenarios and in both 2040 and 2070 in B1 scenario. In the 50-75 cm, Solonchaks follow the same pattern as Planosols with similar values of SOC stocks decreases. Nevertheless, in the upper layers (0-25 cm and 25-50 cm) depletion of SOC occur at a lower rate than in Planosols.

Changes in SOC contents for each land use and soil type

Future changes in SOC contents for each land use and soil group are shown in Table 6.6 (for cultivated areas) and Table 6.7 (for natural areas). Under “arable land” and “permanent crops” Arenosols and Solonchaks show largest decreases, particularly in B1 scenario for 2070 and in A2 scenario for 2040 and 2100.

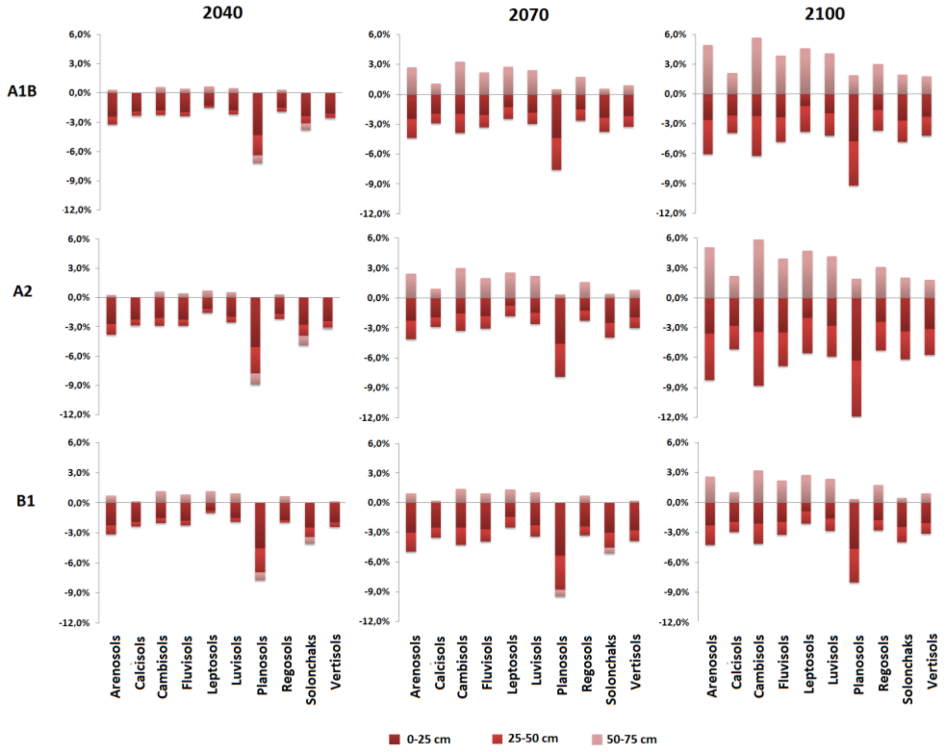


Figure 6.4. Soil organic C stocks in climate change SRES scenarios in different periods (2040, 2070 and 2100) for each soil group at different soil depths (0-25, 25-50, 50-75 cm).

Planosols under “arable land” show large changes in SOC content but only one soil profile is included in this soil-land use combination. Among agricultural uses, “heterogeneous agricultural areas” are the most affected with SOC decreases between 22.3 and 28.6% in Fluvisols (considering all SRES scenarios). In “forest”, Cambisols show SOC content losses between 12.8 and 15.1% in 2070 and between 12.4 and 24.0% in 2100. Although decreases of SOC stocks are not among the largest, it should be considered that this soil-land use combination covers 10.7% of the study area, the largest among the different associations of land use and soil types. Other soil groups under “forest” with important losses in of SOC stocks are Leptosols and Arenosols.

The consequences of climate change in Regosols under “scrub and/or herbaceous associations” and “open spaces with little or no vegetation” are remarkable. In 2040, the model application in Regosols under “open spaces” predicts SOC losses between 49.4 and 53.5% in 2040, 57.1 and 67.4% in 2070 and 58.8 and 80.4 % in 2100. B1 scenario projections enclose the highest losses in this combination of soil type and land use.

Table 6.6. Projected soil organic C contents (Mg/ha) and percentage of change of cultivated areas in climate change scenarios (A1B, A2 and B1). N: number of profiles; S: area (ha). AR: Arenosols, CL: Cambisols, CM: Cambisols, FL: Fluvisols, LP: Leptosols, LV: Luvisols, PL: Planosols, RG: Regosols, SC: Solonchaks, VR: Vertisols.

Land use				**A1B**			**A2**			**B1**		
Soil group	**N**	**S**	**2000**	**2040**	**2070**	**2100**	**2040**	**2070**	**2100**	**2040**	**2070**	**2100**
Arable land												
AR	6	67,2 (0,1%)	45,2±13,2	43,2±12,4 (-4,5%)	42,3±11,8 (-6,5%)	41,7±11,6 (-7,7%)	42,5±11,9 (-6,1%)	42,0±11,7 (-7,2%)	40,2±11,5 (-11,1%)	42,8±11,9 (-5,4%)	41,3±11,7 (-8,8%)	42,1±11,7 (-6,8%)
CL	72	418,4 (0,5%)	70,0±30,3	67,6±30,0 (-3,4%)	66,5±29,78 (-5%)	66,0±29,7 (-5,8%)	66,8±29,8 (-4,6%)	66,3±29,8 (-5,3%)	64,3±29,7 (-8,1%)	67,3±29,8 (-3,8%)	65,6±29,7 (-6,2%)	66,5±29,8 (-5%)
CM	43	4430,5 (5,1%)	47,1±34,3	45,7±34,0 (-3%)	44,9±34,1 (-4,6%)	44,3±34,2 (-5,8%)	45,2±34,0 (-4%)	44,8±34,0 (-4,8%)	42,7±34,2 (-9,3%)	45,8±34,0 (-2,8%)	44,2±34,0 (-6,2%)	44,9±34,1 (-4,5%)
FL	27	1437,7 (1,7%)	65,4±18,7	63,3±18,6 (-3,2%)	62,4±18,5 (-4,6%)	62,0±18,4 (-5,2%)	62,6±18,5 (-4,3%)	62,3±18,5 (-4,8%)	60,4±18,4 (-7,7%)	63,1±18,5 (-3,5%)	61,5±18,5 (-6%)	62,5±18,5 (-4,5%)
LP	16	257,2 (0,3%)	66,8±46,6	65,0±46,4 (-2,7%)	64,5±46,6 (-3,4%)	64,0±46,6 (-4,2%)	64,7±46,6 (-3,1%)	64,3±46,5 (-3,7%)	62,3±46,6 (-6,6%)	65,2±46,5 (-2,3%)	63,6±46,5 (-4,7%)	64,4±46,6 (-3,5%)
LV	26	1521 (1,8%)	50,8±23,1	48,7±22,9 (-4,2%)	48,0±23,0 (-5,5%)	47,5±23,1 (-6,5%)	48,2±22,9 (-5,1%)	47,8±22,9 (-5,9%)	45,9±23,1 (-9,7%)	48,8±22,9 (-4%)	47,2±22,9 (-7,2%)	48,0±23,0 (-5,5%)
PL	1	725,4 (0,8%)	64,5	61,5 (-4,7%)	60 (-6,9%)	59,4 (-7,9%)	60,3 (-6,6%)	59,8 (-7,2%)	57,8 (-10,5%)	60,7 (-5,9%)	59 (-8,5%)	59,9 (-7,1%)
RG	53	2037,7 (2,4%)	61,1±22,1	59,4±21,9 (-2,8%)	58,7±21,8 (-3,9%)	58,2±21,8 (-4,7%)	58,9±21,9 (-3,6%)	58,5±21,9 (-4,3%)	56,6±21,8 (-7,3%)	59,4±21,9 (-2,7%)	57,8±21,8 (-5,4%)	58,7±21,9 (-4%)
SC	3	910,5 (1,1%)	48,3±22,3	46,6±21,4 (-3,6%)	45,1±21,2 (-6,7%)	44,4±21,0 (-8,2%)	45,2±21,2 (-6,4%)	44,8±21,1 (-7,3%)	42,8±21,0 (-11,4%)	45,7±21,1 (-5,6%)	44,0±21,0 (-9%)	45,0±21,2 (-7%)
VR	33	3645,3 (4,2%)	66,7±19,1	64,5±18,9 (-3,2%)	63,6±18,9 (-4,6%)	63,1±18,9 (-5,3%)	63,8±18,9 (-4,3%)	63,4±18,9 (-4,8%)	61,5±18,9 (-7,7%)	64,4±18,9 (-3,4%)	62,8±18,8 (-5,8%)	63,6±18,9 (-4,5%)
Permanent crops												
AR	5	24,6 (0%)	33,3±13,8	31,0±14,2 (-6,8%)	30,8±14,1 (-7,6%)	30,3±14,1 (-9,1%)	31,0±14,0 (-6,9%)	30,8±14,0 (-7,6%)	28,7±14,2 (-13,9%)	31,7±13,9 (-4,7%)	30,1±14,1 (-9,6%)	30,9±14,1 (-7,1%)
CL	49	118,9 (0,1%)	62,3±20,8	60,9±21,3 (-2,2%)	60,1±21,5 (-3,5%)	59,5±21,6 (-4,4%)	60,2±21,5 (-3,3%)	59,9±21,6 (-3,8%)	57,9±21,6 (-6,9%)	60,8±21,5 (-2,4%)	59,2±21,5 (-5%)	60,1±21,5 (-3,5%)
CM	23	7254,2 (8,4%)	53,7±18,9	52,1±19,3 (-3%)	51,6±19,7 (-4%)	51,1±19,8 (-4,9%)	51,7±19,6 (-3,7%)	51,5±19,7 (-4,2%)	49,5±19,8 (-7,8%)	52,3±19,6 (-2,6%)	50,7±19,7 (-5,5%)	51,6±19,7 (-4%)
FL	3	953,6 (1,1%)	28,6±2,4	27,7±1,6 (-3,2%)	27,5±1,3 (-3,9%)	27,0±1,1 (-5,4%)	27,8±1,2 (-2,8%)	27,5±1,0 (-3,9%)	25,4±1,1 (-11,2%)	28,4±0,9 (-0,5%)	26,8±1,1 (-6,1%)	27,5±1,2 (-3,7%)
LP	22	542,7 (0,6%)	55,4±21,4	54,2±21,3 (-2,1%)	53,8±20,9 (-2,8%)	53,4±20,9 (-3,6%)	54,1±20,9 (-2,3%)	53,7±20,9 (-3%)	51,8±20,8 (-6,5%)	54,7±20,9 (-1,2%)	53,1±20,9 (-4,1%)	53,9±20,9 (-2,6%)
LV	32	2380,1 (2,8%)	56,7±33,3	55,0±32,8 (-2,9%)	54,5±32,7 (-3,8%)	54,0±32,8 (-4,6%)	54,7±32,7 (-3,5%)	54,3±32,7 (-4,1%)	52,5±32,7 (-7,4%)	55,2±32,6 (-2,5%)	53,7±32,6 (-5,3%)	54,5±32,7 (-3,8%)
RG	59	3868,2 (4,5%)	56,8±27,3	55,2±27,3 (-2,8%)	54,6±27,5 (-3,8%)	54,1±27,5 (-4,7%)	54,9±27,5 (-3,3%)	54,5±27,5 (-4%)	52,5±27,5 (-7,5%)	55,5±27,5 (-2,3%)	53,9±27,5 (-5,1%)	54,7±27,4 (-3,7%)
SC	1	10,6 (0%)	55,2	51,9 (-6%)	50,12 (-9,2%)	49,2 (-10,8%)	50,5 (-8,5%)	50 (-9,3%)	47,8 (-13,4%)	50,9 (-7,8%)	49,2 (-10,9%)	50,1 (-9,1%)
VR	14	1625,7 (1,9%)	61,2±15,0	59,4±14,5 (-2,9%)	58,8±14,3 (-3,9%)	58,4±14,3 (-4,6%)	59,0±14,3 (-3,5%)	58,7±14,3 (-4%)	56,8±14,3 (-7,2%)	59,7±14,2 (-2,5%)	58,0±14,2 (-5,1%)	58,9±14,3 (-3,6%)
Heterogeneous agricultural areas												
AR	9	24,3 (0%)	43,5±10,9	40,6±9,6 (-6,6%)	39,8±9,3 (-8,5%)	39,1±9,2 (-10,2%)	40,2±9,3 (-7,5%)	39,9±9,3 (-8,9%)	37,4±9,2 (-13,9%)	40,7±9,3 (-6,3%)	39,0±9,2 (-10,2%)	39,7±9,3 (-8,6%)
CL	23	323,6 (0,4%)	64,5±20,7	62,1±20,6 (-3,8%)	61,2±20,6 (-5,2%)	60,6±20,5 (-6%)	61,4±20,7 (-4,8%)	61,0±20,6 (-5,5%)	59,0±20,5 (-8,6%)	62,0±20,7 (-4%)	60,3±20,7 (-6,6%)	61,1±20,6 (-5,3%)
CM	72	6364,8 (7,4%)	22,9±19,3	20,9±19,0 (-8,8%)	20,0±19,0 (-13%)	19,2±19,1 (-16,4%)	20,5±18,9 (-10,4%)	20,0±18,9 (-12,8%)	17,4±19,1 (-24%)	21,1±18,9 (-8,1%)	19,5±18,9 (-15,1%)	20,1±19,0 (-12,4%)
FL	13	597 (0,7%)	41,3±30,3	32,9±32,5 (-20,4%)	31,9±32,6 (-22,7%)	31,2±32,6 (-24,5%)	32,5±32,6 (-21,3%)	32,0±32,6 (-22,5%)	29,5±32,6 (-28,6%)	33,1±32,6 (-19,9%)	31,4±32,6 (-23,9%)	32,1±32,5 (-22,3%)
LP	59	352,1 (0,4%)	42,2±40,7	39,6±40,3 (-6,1%)	38,7±40,2 (-8,3%)	37,9±40,2 (-10,1%)	39,2±40,2 (-6,9%)	38,6±40,1 (-8,4%)	36,2±40,3 (-14,1%)	39,7±40,2 (-5,7%)	38,1±40,1 (-9,6%)	38,7±40,2 (-8,1%)
LV	27	860,7 (1%)	28,3±18,3	27,1±18,0 (-4,3%)	26,3±18,0 (-6,9%)	25,7±18,1 (-9,3%)	26,6±18,1 (-5,9%)	26,2±17,9 (-7,4%)	24,0±18,1 (-15,1%)	27,2±17,9 (-3,9%)	25,6±17,9 (-9,5%)	26,3±18,0 (-7,1%)
RG	27	1640,8 (1,9%)	42,9±23,0	39,0±23,2 (-9,1%)	38,2±23,4 (-10,8%)	37,5±23,4 (-12,5%)	38,6±23,4 (-9,9%)	38,1±23,3 (-11,2%)	35,9±23,5 (-16,3%)	39,2±23,4 (-8,6%)	37,5±23,3 (-12,5%)	38,2±23,4 (-10,8%)
SC	2	80,3 (0,1%)	69,9±21,6	66,3±22,2 (-5,1%)	64,8±22,4 (-7,3%)	64,1±22,3 (-8,3%)	64,8±22,4 (-7,2%)	64,5±22,5 (-7,8%)	62,5±22,3 (-10,6%)	65,2±22,5 (-6,7%)	63,7±22,4 (-9%)	64,7±22,5 (-7,5%)
VR	20	975,9 (1,1%)	64,1±19,4	61,3±19,5 (-4,4%)	60,3±19,1 (-5,9%)	59,7±19,0 (-6,9%)	60,5±19,1 (-5,6%)	60,1±19,0 (-6,3%)	58,1±19,0 (-9,4%)	61,0±19,0 (-4,8%)	59,4±19,0 (-7,4%)	60,2±19,1 (-6%)

Table 6.7. Projected soil organic C contents (Mg/ha) and percentage of change of natural areas in climate change scenarios (A1B, A2 and B1). N: number of profiles; S: area (ha). AR: Arenosols, CL: Cambisols, CM: Cambisols, FL: Fluvisols, LP: Leptosols, LV: Luvisols, PL: Planosols, RG: Regosols, SC: Solonchaks, VR: Vertisols.

Land use				**A1B**			**A2**			**B1**		
Soil group	**N**	**S**	**2000**	**2040**	**2070**	**2100**	**2040**	**2070**	**2100**	**2040**	**2070**	**2100**
Forest												
AR	26	221 (0,3%)	38,0±18,2	35,0±18,0 (-7,7%)	34,2±18,0 (-9,9%)	33,5±18,0 (-11,7%)	34,5±17,8 (-9%)	34,1±17,9 (-10,2%)	32,0±18,0 (-15,7%)	35,0±17,8 (-7,6%)	33,4±17,8 (-12,1%)	34,2±17,8 (-10%)
CL	8	36,8 (0%)	74,3±55,3	70,9±54,7 (-4,5%)	70,0±54,1 (-5,7%)	69,4±54,0 (-6,6%)	70,7±54,6 (-4,8%)	69,9±54,0 (-5,9%)	67,7±53,9 (-8,8%)	71,3±54,4 (-4%)	69,4±54,3 (-6,6%)	70,1±54,2 (-5,6%)
CM	52	9229,7 (10,7%)	44,1±38,1	40,8±37,5 (-7,5%)	39,5±37,4 (-10,5%)	38,7±37,4 (-12,2%)	40,2±37,4 (-8,7%)	39,4±37,3 (-10,7%)	37,0±37,5 (-16%)	40,7±37,4 (-7,7%)	38,9±37,3 (-11,7%)	39,6±37,4 (-10,1%)
FL	15	452,9 (0,5%)	36,8±22,6	34,6±21,9 (-5,8%)	33,8±21,9 (-8%)	33,2±21,9 (-9,7%)	34,3±21,9 (-6,8%)	33,7±21,9 (-8,2%)	31,6±22,0 (-14%)	34,8±21,8 (-5,3%)	33,1±21,8 (-9,9%)	33,9±21,9 (-7,8%)
LP	131	2046,3 (2,4%)	58,2±59,2	52,3±61,9 (-10,1%)	48,4±79,7 (-16,9%)	47,7±79,6 (-18,2%)	49,0±79,7 (-15,8%)	48,3±79,7 (-17%)	46,0±79,6 (-21%)	49,5±79,7 (-15%)	47,8±79,7 (-17,9%)	48,5±79,7 (-16,8%)
LV	36	1159,4 (1,3%)	54,1±40,7	52,2±40,4 (-3,6%)	51,4±40,2 (-5,1%)	50,7±40,2 (-6,3%)	52,0±40,4 (-4%)	51,3±40,2 (-5,3%)	49,2±40,2 (-9,2%)	52,4±40,4 (-3,1%)	50,8±40,3 (-6,3%)	51,4±40,3 (-5%)
RG	111	4464,2 (5,2%)	53,5±46,7	49,2±46,3 (-8,1%)	48,1±46,3 (-10,1%)	47,4±46,3 (-11,5%)	48,8±46,3 (-8,8%)	48,1±46,3 (-10,2%)	45,7±46,3 (-14,6%)	49,3±46,3 (-7,9%)	47,6±46,3 (-11,1%)	48,2±46,3 (-9,9%)
SC	1	36,8 (0%)	33,9	32,6 (-3,8%)	31,7 (-6,4%)	30,9 (-8,8%)	32 (-5,7%)	31,5 (-7%)	29,2 (-13,8%)	32,7 (-3,6%)	30,8 (-9,1%)	31,7 (-6,4%)
Scrub and/or herbaceous vegetation associations												
AR	17	198 (0,2%)	43,6±20,1	40,1±20,3 (-8%)	39,1±20,5 (-10,3%)	38,5±20,6 (-11,8%)	39,4±20,3 (-9,6%)	38,9±20,3 (-10,8%)	36,9±20,6 (-15,5%)	40,0±20,2 (-8,4%)	38,3±20,3 (-12,3%)	39,1±20,3 (-10,3%)
CL	11	822,5 (1%)	73,8±29,0	70,7±29,3 (-4,2%)	69,6±29,0 (-5,8%)	68,9±28,9 (-6,7%)	70,4±29,1 (-4,6%)	69,4±28,9 (-6%)	67,2±28,8 (-8,9%)	70,9±29,1 (-4%)	68,9±29,1 (-6,6%)	69,7±29,0 (-5,6%)
CM	31	8180,5 (9,5%)	38,6±22,4	35,9±22,0 (-7,1%)	34,8±22,0 (-9,8%)	34,2±21,9 (-11,5%)	35,5±21,9 (-8,2%)	34,8±21,9 (-10%)	32,6±21,9 (-15,7%)	35,9±21,9 (-7%)	34,3±21,9 (-11,2%)	35,0±21,9 (-9,5%)
FL	8	730,3 (0,8%)	54,3±24,4	51,6±23,1 (-5%)	50,4±23,3 (-7,2%)	49,8±23,3 (-8,2%)	50,6±23,2 (-6,7%)	50,3±23,1 (-7,4%)	48,1±23,3 (-11,4%)	51,2±23,2 (-5,7%)	49,6±23,2 (-8,7%)	50,4±23,2 (-7,2%)
LP	75	3878,7 (4,5%)	65,2±56,5	61,4±56,5 (-5,8%)	60,6±56,3 (-7%)	59,9±56,3 (-8%)	61,0±56,4 (-6,3%)	60,4±56,3 (-7,3%)	58,3±56,3 (-10,5%)	61,5±56,3 (-5,6%)	59,9±56,3 (-8,1%)	60,6±56,3 (-7%)
LV	13	938,7 (1,1%)	76,7±39,3	73,5±39,4 (-4,2%)	72,2±38,9 (-5,9%)	71,6±38,8 (-6,6%)	72,9±39,2 (-5%)	72,1±38,9 (-6%)	70,0±38,9 (-8,7%)	73,3±39,1 (-4,4%)	71,6±38,9 (-6,7%)	72,2±38,9 (-5,8%)
PL	1	211,9 (0,2%)	51,3	47,8 (-6,9%)	46,3 (-9,7%)	45,8 (-10,7%)	46,6 (-9,1%)	46,1 (-10,2%)	44,1 (-14%)	47,2 (-8%)	45,3 (-11,7%)	46,3 (-9,7%)
RG	53	4370,2 (5,1%)	55,1±31,9	53,5±32,6 (-2,8%)	52,4±32,6 (-4,8%)	51,78±32,7 (-6%)	52,9±32,6 (-3,9%)	52,2±32,6 (-5,2%)	50,1±32,8 (-8,9%)	43,4±72,0 (-21,1%)	41,8±71,9 (-24,2%)	42,5±71,9 (-22,9%)
VR	7	627,1 (0,7%)	56,9±26,9	54,3±26,7 (-4,6%)	54,1±25,9 (-5%)	53,7±25,7 (-5,8%)	54,8±26,2 (-3,8%)	54,1±25,6 (-5%)	52,1±25,8 (-8,4%)	55,3±26,0 (-2,8%)	53,5±25,8 (-6%)	54,2±25,8 (-4,8%)
Open spaces with little or no vegetation												
LP	4	91,6 (0,1%)	25,2±20,2	20,8±21,7 (-17,5%)	19,9±21,6 (-21,3%)	19,3±21,8 (-23,4%)	20,2±21,8 (-20%)	19,7±21,7 (-22,1%)	17,9±21,8 (-29,2%)	20,6±21,8 (-18,5%)	19,1±21,8 (-24,5%)	19,7±21,8 (-21,8%)
LV	1	20,4 (0%)	17,8	16,9 (-4,8%)	16,7 (-6%)	15,8 (-10,9%)	16,9 (-4,8%)	16,3 (-8%)	14,3 (-19,6%)	17,5 (-1,4%)	15,9 (-10,4%)	16,5 (-7,1%)
RG	2	4370,2 (5,1%)	8,5±0,6	4,2±0,1 (-50,2%)	3,6±0,7 (-57,1%)	3,0±0,6 (-64,5%)	3,9±0,7 (-53,5%)	3,4±0,8 (-59,3%)	1,7±0,7 (-80,4%)	4,3±0,7 (-49,4%)	2,8±0,8 (-67,4%)	3,5±0,6 (-58,8%)
Maritime wetlands												
AR	2	10,9 (0%)	36,9±13,6	23,5±21,2 (-36,3%)	22,8±21,0 (-38,3%)	22,1±20,9 (-40,2%)	22,8±21,0 (-38,2%)	22,3±20,9 (-39,5%)	20,3±20,8 (-44,9%)	23,4±20,8 (-36,7%)	21,6±20,8 (-41,4%)	22,6±20,9 (-38,7%)
FL	1	61,5 (0,1%)	44,7	41,1 (-8%)	40,4 (-9,6%)	39,8 (-10,9%)	40,4 (-9,4%)	39,9 (-10,7%)	38,2 (-14,5%)	41,2 (-7,9%)	39,4 (-11,7%)	40,3 (-9,8%)
RG	1	16,5 (0%)	17,1	15,3 (-10,4%)	14,2 (-16,9%)	13,7 (-19,9%)	14,2 (-15,6%)	14 (-18,5%)	12,5 (-27,1%)	14,9 (-12,7%)	13,4 (-21,9%)	14,3 (-16,6%)
SC	10	525 (0,6%)	78,4±	74,9±53,3 (-4,5%)	74,3±53,3 (-5,3%)	74,9±53,2 (-4,4%)	74,3±53,3 (-5%)	72,8±53,3 (-7,2%)	75,4±53,2 (-3,9%)	73,8±53,3 (-5,9%)	74,8±53,2 (-4,7%)	74,8±53,2 (-4,7%)

In maritime wetlands, future climate will affect extensively the SOC contents of Arenosols. More than 40% of the current SOC content will be lost in 2070 and 2100.

6.4 Discussion

6.4.1 Soil C modelling in climate change scenarios

A number of studies have investigated SOC changes in future climate scenarios applying Climate Models (GCMs) forced by IPPC SRES scenarios (Berthelot et al., 2005; Lucht et al., 2006; Wan et al., 2011). Among soil carbon models, one the most widely used is Century SOC model (Parton et al., 1987; 1992) which has been applied at site and regional scales (Álvaro-Fuentes at al., 2012; Shrestha et al., 2009; Tornquist et al., 2009). Likewise, the Rothamsted carbon model (RothC; Coleman and Jenkinson, 1999) has been widely used to estimate the SOC change in response to climate change or land use management alterations (Guo et al., 2007; Smith et al., 2005; Xu et al., 2011). In the past years these models have been implemented in the Mediterranean region to determine SOC changes in future climate scenarios. In Italy, Mondini et al. (2012) applied Roth-C model to evaluate SOC stocks between 2001 and 2100. They used 3 different GCMs, namely HadCM, PCM and GCM2 (Mitchell et al., 2004) forced by 4 SRES scenarios (A1F1, A2, B1 and A2) described in Nakicenovic et al (2000). In the same region, Lugato and Berti (2008) projected future climate simulations from 2008 to 2080 using Century SOC model and four GCMs forced by four IPPC SRES.

A recent study in northeast Spain (Alvaro Fuentes et al., 2012) reported SOC changes between 2007 and 2087. In their work, they used the Century SOC model in the 0-30 cm soil depth over an agricultural area of 40,498 km^2. Climate scenarios considered in their work were ECHAM4 and CGCM2 forced by A2 and B2 SRES emissions. Likewise, Álvaro-Fuentes and Paustian (2011) applied Century SOC model in different semiarid areas of Spain at field and regional scale level under the same climate change scenarios. A comprehensive pan-European assessment of changes in SOC stocks was carried out by Smith et al. (2005). They applied the Roth-C model in European croplands and grasslands to project changes in SOC stocks between 1990 and 2080. Four GCMs were used for the projections (HadCM3, CSIRO2, PCM and CGM2; Mitchell et al., 2004) in four SRES scenarios (A1F1, A2, B1 and B2). Nonetheless, few studies considering the different soil sections in projected SOC stocks have been undertaken in Mediterranean areas. Generally, most of the research on modelling SOC dynamics have focused on the upper layer without specification of the vertical distribution such as the Century SOC model (Parton et al., 1987) or EPIC (Izaurralde et al., 2006). Although a number of studies have developed models for soil depth up to 1 metre such as Roth-C model (Coleman and Jenkinson, 1999) or Yasso (Liski et al, 2005), these tools are specifically designed for either agricultural areas or forests, but not for both natural and transformed land use types. Several works have proved that deeper layers in the soil profile are able to store a substantial amount of organic C (Batjes, 1996; Jobbagy and Jackson, 2000; Muñoz-Rojas et al., 2012; Tarnocai et al., 2009). Therefore, new methods and tools are necessary to explore the potential impacts of future climate changes in SOC contents at different soil depths and land use types.

This study applies four sub models of a SOC model (CarboSOIL) in order to quantify SOC at different soil depths. The model is driven by BCCR-BCM2, CNRMCM3 and ECHAM5 climate predictions with three IPCC forcing scenarios (A1B. A2 and B2) to predict the effects of climate change on SOC contents and sequestration. The methodology is easily applicable to other Mediterranean areas with available data on climate, site, soil and land use. Additionally, coupling detailed spatial databases with CarboSOIL model allows measuring regional SOC stocks and sequestration potential.

6.4.2 Predicted future SOC stocks under climate change scenarios

Our research provides with the first estimates of SOC contents and stocks in Southern Spain in future scenarios and allows analysing C sequestration trends associated to climate change. Overall, our results suggest that climate change will have a negative impact on SOC contents in the upper layers of the soil section. According to our findings, annual precipitation has an important effect on SOC contents. In the top soil layers, SOC stocks decrease when diminishing rainfall, opposite to the increases in deeper layers. Additionally, although climate change scenarios predict a decrease in annual precipitation, more intensive rainfall events are expected. These events are likely to change soil structure and soil quality, particularly in upper layers, which together with SOC depletion makes the soil more susceptible to erosion processes (Christensen et al., 2011).

Increasing summer temperatures will affect the SOC pools up to 50 cm with a consequent depletion of this pool, mainly in sensitive land areas such as salt marshes and fruit trees and berries plantations. On the other hand, the sensitivity analysis suggests that winter temperatures are desirable for increasing SOC contents. It has been reported that increasing temperatures will accelerate C decomposition due to the rise of temperatures (Zhang et al., 2005). Consequently, direct climate impacts on croplands and grasslands soils will tend to decrease SOC stocks all over Europe (Smith et al., 2005). However, temperature sensitivity of soil carbon decomposition depends on the soil type. Although temperature clearly affects decomposition of a labile SOC fraction, a significant portion of SOC is influenced by other environmental factors (Davidson and Janssens, 2006). The effects of climate change on SOC stocks will be particularly severe in Planosols, Solonchaks and Regosols. In Regosols under “scrub and/or herbaceous associations” and “open spaces with little or no vegetation" losses of SOC up to 80.4 % are expected in 2100. Theses land use-soil type combinations occupy 8740.4 ha (more than 10% of the study area); therefore, especial attention should be paid to these areas.

Despite the diversity of SOC contents associated to different climate change scenarios our results show an evident decrease of SOC in Southern Spain. In the total soil profile (first 75 cm), SOC changes between 2000 and 2100 vary from -3.4 % in CNRMCM3-B1 to -13.0% in CNRMCM3-A2. Our results are generally in agreement with the works of Mondini et al. (2012), Smith et al. (2005), Wan et al. (2011) which applied Roth-C model and projected a decrease of SOC during the 21st century. Absolute values cannot be directly compared due to the differences in the soil sections but percentage change can be contrasted.

Smith et al. (2005) predicted SOC changes between -10% and -14% of the 1990 mean SOC stock of European croplands and between -6 and -10% of the 1990 mean SOC stock of European grasslands. Wan et al. (2011) reported a percentage decrease of 5.5%, 12% and 15% in SOC by the years 2020, 2050 and 2080 respectively in northern China. In their study, Mondani et al. (2012) projected SOC losses between 2001 and 2100 with values ranging from -4.4% in the PCM-B1 scenario to -11.5% in the CGM2-A1F1 scenario in consistence with our results. Álvaro-Fuentes and Paustian, (2011) and Álvaro-Fuentes et al. (2012) predicted increases in SOC contents of Spanish agroecosystems under future climate change scenarios which differ from our simulations. However, in both studies they applied the Century model which account SOC stocks only in the upper 30 cm.

6.4.3 Uncertainties and limitations

Changes in land use are expected in the future decades at global, regional and local scales these. However, in our projections land use remains invariable between the 2000-2100 periods. The purpose of this study is to apply and test CarboSOIL in climate change scenarios and to assess changes in SOC in response to climate change; therefore, land uses are considered constant over the simulation period. Results obtained from application of simulation models in climate change scenarios are related to different sources of uncertainty associated mainly with the model imprecision and the climate scenarios. CarboSOIL is an empirical model based on regression/correlation techniques and, although these statistical procedures are not able to explain complex mechanisms within the soil system, this type of models are useful tools to identify different drivers of SOC dynamics and perform projections of SOC stocks (Viaud et al., 2010). According to the results obtained in the validation process, CarboSOIL model has proved to be consistent and measured values were well correlated with the modelled values. Sensitivity analysis evidence the ability of the model to identify cause-effect relationships. Moreover, the advantages of CarboSOIL model include easiness in application and simplicity of interpretation.

A range of model projections is considered in this study. We obtained different results of SOC contents associated to different climate predictions which highlight the uncertainty in future climate scenarios. In climate projections, uncertainties can be related to emissions, climatic drivers (e.g., carbon cycle), climate sensitivity and adaptive capacity, among others (Van Vuuren et al., 2011). In areas of complex topography like the Mediterranean region, application of GCMs might result in considerable biases in the prediction of precipitation and temperature (Giorgi and Lionello, 2008). In particular precipitation involves local processes of larger complexity than temperature and projections are usually less robust than those for temperature. In our study the climate data used had been transformed with a regionalization technique performed by REDIAM. Thus, the climate change scenarios are better adjusted to the physiographic environment of the study area. The climate system suffers variations on different timescales. In this work we consider time periods of 30 years, given that this time-slice has been traditionally considered to assess climate factors with substantial confidence (IPPC, 2007; Christensen et al., 2011).

6.5 Conclusions

Predicting SOC stocks and simulating SOC dynamics has become a relevant issue because of the role that SOC pools can play reducing the rate of increase of atmospheric CO_2 concentration. Worldwide, a large amount of C in soil pools has been lost due to inadequate soil management. This trend is likely to continue in the next future due to global warming and climate change. However, this depleted C pools could be refilled with an appropriate management. It is essential to predict SOC stocks in future climate scenarios to establish adequate land use and management strategies in accordance with different soil types at different soil depths. Several SOC models in combination with climate change scenarios have been developed to address this matter but new tools are needed to improve SOC stocks predictions.

In our study we apply CarboSOIL model in climate change scenarios to determine SOC changes in 2040 (2011-2040), 2070 (2041-2070) and 2100 (2071-2100) in a Mediterranean region (Southern Spain). The model has proved to be consistent and measured values were well correlated with the modelled values. Linking CarboSOIL model to detailed spatial databases allows measuring regional SOC stocks and sequestration potential. This research provides with SOC contents and stocks estimates in Southern Spain in future climate scenarios, assessing C sequestration trends associated to climate change. Our results show that climate change will have a negative impact on SOC contents in the upper layers of the soil section (0-25 and 25-50 cm). In particular, SOC contents are expected to decrease severely in the medium-high emissions A2 scenario by 2100. Regosols under “open spaces or areas with little vegetation” cover and sensitive land areas such as “salt marshes” and “fruit trees and berries plantations” will be largely affected. The methodology can be easily applied to other Mediterranean areas with available data on soil, site, land use and climate factors. This study might support decision-making in land management and climate adaptation strategies in Mediterranean regions.

CHAPTER 7

GENERAL DISCUSSION

Carbon sequestration in a global change framework

In a context of growing population and changing climate, the main challenges of our era are to ensure food security and to maintain and preserve the resilience of both natural and agricultural ecosystems. During the last years, the need for accurate information on SOC contents at the European, national or regional level has increased due to the importance of SOC stocks for sustainable use of natural resources (Phachomphon et al., 2010). Accordingly, different European Union (EU) Policies, as the 6th Environment Action Programme (European Soil Thematic Strategy), the Common Agricultural Policy, etc., call for detailed soil information within the EU. Other initiatives, such as the Millennium Ecosystem Assessment, funded internationally by the World Bank, the United Nations Global Environment Facility, etc., aim to determine the state of the earth's ecosystems, trying to take into consideration all global problems and the interactions among them.

However, besides concerns about environmental problems such as soil degradation and soil contamination, information on SOC stocks is necessary to assess the potential role of soils as CO_2 sinks. The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) is the first international agreement attempting to mitigate global climate change through reduction in net Greenhouse Gases (GHG) emissions. Under Article 3, the Parties included in Annex I of Kyoto Protocol agree that they will reduce their emissions of such gases by at least 5 percent below 1990 levels in the first commitment period from 2008 to 2012. Net changes in GHG emissions by sources and removals of CO_2 through direct human-induced LULUCF activities, such as afforestation, reforestation and deforestation (Article 3.3) can be used to meet emission reduction targets of parties that ratified the UNFCCC. Carbon sequestration in agricultural soils is accountable under Article 3.4 of the Kyoto Protocol which states that parties may elect additional human-induced activities related to LULUCF specifically, forest management, cropland management, grazing land management and revegetation, to be included in their accounting of anthropogenic GHG emissions and removals. Other international policies are being developed in forest conservation for GHG mitigation through the Global Environment Facility (GEF) and international financial institutions like the World Bank (Carbon Partnership Facility) and the Asian Development Bank. In 2007, the European Commission developed 'An Energy Policy for Europe', which also provides a framework to develop, research and invest in carbon sequestration.

Although most of the current mechanisms only apply to carbon sequestration (i.e., the additional storage of carbon over time), there is growing interest in financial incentives to avoid release of C from ecosystems in the first place, the so-called "Reducing Emissions from Deforestation and Forest Degradation" (REDD)(Mollicone et al. 2007). This option, accepted during the last meeting of the parties to the UNFCCC, is likely to be included in a post-2012 international climate agreement. REDD+ is a version that can deliver "co-benefits" such as biodiversity conservation and poverty alleviation. In these circumstances, information about C storage and sequestration is essential to support decisions in land management and climate adaption strategies by governments, NGOs, and businesses. One of the objectives of this thesis is to contribute to a better knowledge of the effects of LULCs on terrestrial carbon dynamics in Mediterranean systems (Figure 7.1). During the last 50 years, several transformations have occurred in the Mediterranean region, especially an intensification of the agricultural systems and abandonment of less productive areas (Chapter 2). These changes have contributed in many cases to the depletion of the carbon pool which might be replenished with an adequate use and management (Smith, 2000; Smith et al., 2004). However, most of the studies carried out in Mediterranean areas regarding soil carbon dynamics have focused on the topsoil. Our approach intended to take into account the different processes along the soil profile as well as the variety of land uses and main soil types (Chapter 3 and Chapter 4). Previous studies conducted in Mediterranean areas regarding vegetation and soil carbon assessment have been developed based on expensive methods, difficult to apply at large scale (Garcia et al., 2010). With this thesis, new methods are introduced which are cost-effective and easily applicable to other areas.

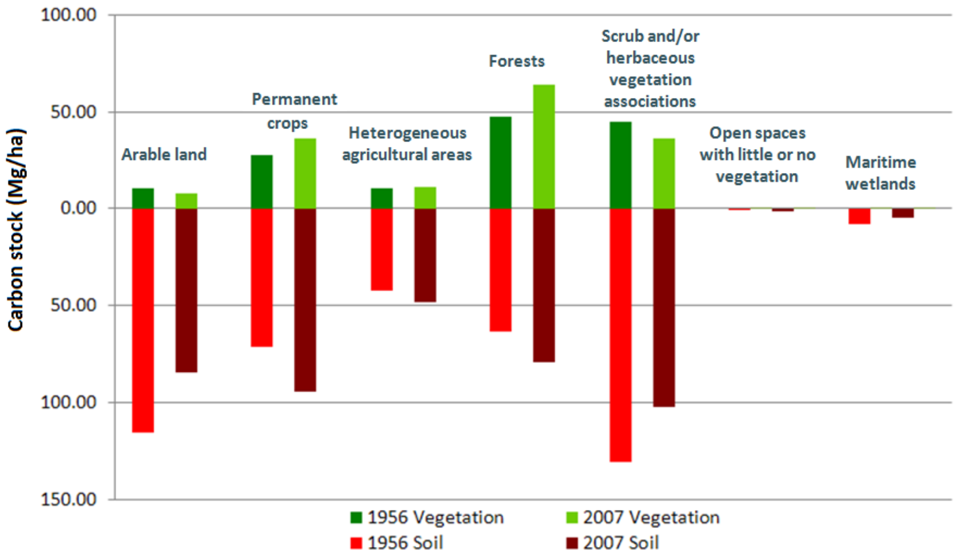


Figure 7.1 Changes in vegetation and soil carbon stocks between 1956 and 2007 for different LU types.

New tools for soil carbon assessment

New strategies and policies within the international framework have been developed for the implementation of agriculture and forestry management practices that enhance carbon sequestration (CS) both in biomass and soils. Thus, several nations are developing new methods or using existing simulation models for carbon accounting (Lokupitiya and Paustian, 2006). Soil C models are able to evaluate present SOC stocks and to predict soil C sequestration trends under different projected scenarios (Kutsch et al., 2009). In the last decades, several SOC models have been developed with different features and for different purposes, but despite the intensive research on these tools, considerable limitations prevail in their application. Some of these models do not consider the subsoil and others are complex and imply a large amount of input data. To fill this gap, this thesis proposes a new model to assess current soil carbon stocks and to predict future changes in multiple scenarios of climate and land use change (Chapter 5). This model (CarboSOIL, Figure 7.2) has been developed as computer application in a GIS environment and is able to determine SOC contents at different soil depths (0-25, 25-50, 50-75 and 0-75 cm). Although modelling is often associated to imprecision, CarboSOIL model has proved to be consistent, and the application in climate change scenarios (Chapter 6) showed that measured values were well correlated with the predicted estimations.

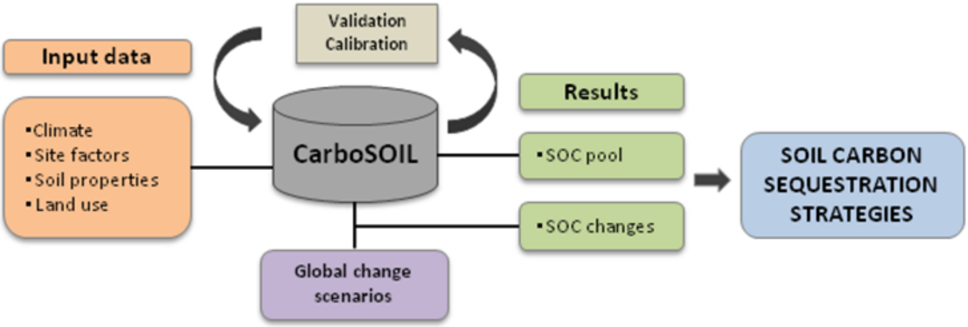


Figure 7.2. CarboSOIL model.

Future prospects for soil carbon in a changing climate

If temperature and atmospheric CO_2 do not stabilize in the future, climate change might cause SOC losses to the atmosphere. Globally, a warming drying future is expected to induce declines in productivity and carbon inputs and increase SOC decomposition rates

(Álvaro-Fuentes et al., 2012; Mondini et al., 2012). The Mediterranean area is among the most sensible regions to climate change, and large increases in temperature as well as drought periods and heavy rainfall events have been forecasted in the next decades (IPPC, 2007). It is essential to the international global change research agenda, the prediction of future SOC stocks and changes. In this thesis, the application of CarboSOIL under a range of climate change scenarios has provided with useful information concerning projected SOC stocks and changes in Southern Spain (Chapter 6). In climate projections there are usually a number of uncertainties related to emissions, climate drivers and sensitivity, etc (Van Vuuren et al, 2011). Therefore, we considered different projections of climate change, obtaining diverse outcomes associated to different climate predictions. Our results highlighted the overall negative impact of climate change on SOC stocks on the upper layers (0-25 and 25-50 cm), yet the deeper layers seems to respond differently.

The information and methods developed in this thesis represent a comprehensive study of LULC change impacts on terrestrial carbon stocks dynamics and soil carbon modelling in Mediterranean areas. Although further studies are needed in the field, this thesis has been an effort to provide a more insightful research concerning carbon sequestration in Mediterranean systems.

CONCLUSIONS AND FUTURE PERSPECTIVES

The research carried out in this thesis comprises the first comprehensive analysis of the impacts of land use changes on terrestrial C stocks at a regional scale in Andalusia (S Spain). A new tool for soil C evaluation in Mediterranean soils (CarboSOIL) has been developed and its application in climate change scenarios has proved the consistency of the model for assessing C sequestration trends associated to changes in future climate.

Land cover changes and terrestrial carbon stocks

Land cover changes in Andalusia, Southern Spain, between 1956 and 2007 have been significant, affecting 33.7% of the area. Land cover transformations in this period have lead to a C sequestration of 17.24 Tg (approx. 0.34 Tg C ha^{-1} yr^{-1}) in the vegetation, mainly due to “afforestation” and “intensification of agriculture” resulting in a total vegetation C stock of 156.08 Tg in 2007 with “coniferous forests” and “olive groves” as major contributors. The proposed methodology for vegetation C assessment is easily applicable to other countries with spatial land use information. In the last 50 years, land use changes in southern Spain have led to a SOC loss of 16.8 Tg, which indicates an average C sequestration rate of approximately 0.33 Tg $year^{-1}$. As a result of “intensification of agriculture” and “deforestation” between 1956 and 2007, SOC stocks decreased in Andalusia. Opposite, remarkable positive rates of change of SOC stocks were obtained in Fluvisols and Luvisols with conversion to “arable land” or “heterogeneous agricultural areas”. Afforestation practices contributed to increase SOC, mostly in the topsoil (first 25 cm) and in total, “forest” contributed to the sequestration of 8.62 Mg ha^{1} of SOC (with a sequestration rate of 25.4%). The converse process (“deforestation”) implied important SOC losses (above 50%). in Cambisols, Luvisols and Regosols. Transformation from “scrub” to “open spaces”, have severely affected SOC contents in Andalusia (southern Spain), mostly in Luvisols and Vertisols.

Current soil organic carbon stocks in Southern Spain

Currently, Cambisols and Regosols are the most common soil types in Andalusia, but Calcisols and Vertisols show the highest SOCC values, above 65 Mg C ha^{-1}. In total, SOC stock is 415 Tg in the upper 75 cm, with 55% stored in the first layer (0-25 cm). The amount of SOC in the first 75 cm was significantly correlated with annual mean temperature, annual mean precipitation and elevation in natural areas.

Modelling soil organic carbon

Out of the different methodologies tested to design a new tool to predict SOC contents in different scenarios, higher predictions have been obtained with MLR techniques and Box-Cox transformation procedures. The model (CarboSOIL), trained in Andalusia and tested in

Valencia has proved its ability to predict SOC at different soil depths (0-25 cm, 25-50 cm, 50-75 cm and 0-75 cm). CarboSOIL, composed by four submodels (CarboSOIL25, CarboSOIL50, CarboSOIL75 and CarboSOIL TOTAL), has been developed as a computer application to be implemented in MicroLEIS DSS. Designed as a spatial tool in a GIS environment for spatial analysis of its inputs/outputs, CarboSOIL have shown its capacity to quantify and understand the distribution of soil carbon

Soil organic carbon in climate change scenarios

Climate change will have a negative impact on SOC contents in the upper layers of the soil section (0-25 and 25-50 cm). SOC stocks are expected to decrease severely under the medium-high emission scenario A2. Regosols under “open spaces or areas with little vegetation cover”, and sensitive areas such as “salt marshes” and “fruit trees and berries plantations” will be largely affected.

This thesis might be useful to support decision-making in land management and climate adaptation strategies in Mediterranean regions. The methodology developed in this research is easily applicable to other Mediterranean areas with available data on climate, site, soil and land use. In this thesis we considered a range of 51 years for the analysis of LULC changes, which is representative of long-term periods; however, additional studies involving short term periods would be helpful for a better knowledge of terrestrial C dynamics. In our future projections of SOC stocks, land use remains invariable since the purpose of the study was to assess changes in SOC stocks in response to climate change. Nonetheless, land use changes are expected in the next decades and further research concerning the impact of these changes on SOC stocks would be of great interest.

CONCLUSIONES Y NUEVAS PERSPECTIVAS

La investigación llevada a cabo en esta tesis constituye el primer análisis exhaustivo de los impactos de los cambios de uso del suelo sobre las reservas de carbono terrestre a escala regional en Andalucía (sur de España). Durante este trabajo se ha desarrollado una nueva herramienta (modelo CarboSOIL) para la evaluación de los contenidos de carbono orgánico de los suelos Mediterráneos. La aplicación de CarboSOIL en escenarios de cambio climático ha demostrado la robustez del modelo a la hora de evaluar las tendencias en el secuestro de carbono asociadas al cambio climático.

Cambios en los usos del suelo y las reservas de carbono terrestre

Durante el período 1956-2007 se han producido importantes cambios en los usos del suelo en Andalucía (sur de España) que han afectado al 33.7% de la región. Las transformaciones producidas en el territorio en este período, han dado lugar a una acumulación de 17.24 Tg C en la vegetación (aproximadamente 0.34 Tg C ha^{-1} $año^{-1}$), principalmente debido a la reforestación y a la intensificación de la agricultura, lo que significa un total de 156.08 Tg de carbono acumulado en la vegetación en el año 2007, principalmente en bosques de coníferas y olivar. La metodología propuesta para el análisis de carbono en la vegetación es fácilmente extrapolable a otros países que dispongan de información espacial de usos del suelo. Los cambios de uso del suelo producidos en los últimos 50 años en el sur de España han supuesto una pérdida de 16.8 Tg de carbono en los suelos, lo que se traduce en una tasa media de pérdida de carbono de 0.33 Tg C ha^{-1} $año^{-1}$, aproximadamente. Como resultado de la intensificación de la agricultura y la deforestación en Andalucía entre 1956 y 2007, los contenidos de carbono orgánico del suelo (COS) se han visto reducidos. Tras la conversión a tierras de cultivo o áreas agrícolas heterogéneas se han observado importantes tasas de acumulación de COS en suelos ampliamente representados como Fluvisoles y Luvisoles. Las prácticas de reforestación han contribuido al aumento del COS, sobre todo en la capa más superficial del suelo (primeros 25 cm), y en total, los bosques han contribuido al aumento de 8.62 Mg ha^{-1} de COS (con una tasa de acumulación del 25.4%). El proceso inverso (deforestación) ha provocado importantes pérdidas de COS en suelos como Cambisoles, Luvisoles y Regosoles (por encima del 50% con respecto a los valores iniciales). La degradación del matorral hacia espacios abiertos o sin vegetación ha afectado negativamente al contenido de COS en Andalucía (sur de España), sobre todo en Luvisoles y Vertisoles.

Contenidos actuales de carbono en los suelos en el sur de España

En la actualidad, Cambisoles y Regosoles son los tipos de suelos con mayor presencia en Andalucía; no obstante, Calcisoles y Vertisoles muestran los valores medios más altos de carbono orgánico, con valores por encima de 65 Mg C ha^{-1}. En total, el contenido de carbono de los principales suelos de Andalucía es de 415 Tg en los primeros 75 cm, con un 55% almacenado en la capa más superficial (0-25 cm). En las áreas naturales de la región de estudio, el contenido en carbono orgánico de los primeros 75 cm del suelo está significativamente correlacionado con la temperatura media anual, la precipitación media anual y la elevación.

Modelización del carbono orgánico del suelo

De las diferentes metodologías examinadas para el diseño una nueva herramienta capaz de predecir el COS en diferentes escenarios, las mejores predicciones se han obtenido con técnicas de regresión múltiple y procesos de transformación Box-Cox. El modelo generado (CarboSOIL) ha sido entrenado en Andalucía y validado en Valencia, demostrando su gran capacidad para predecir el contenido de COS a distintas profundidades (0-25, 25-50, 50-75 y 0-75 cm). El modelo CarboSOIL, compuesto por cuatro submodelos (CarboSOIL25, CarboSOIL50, CarboSOIL75 y CarboSOIL TOTAL), se ha desarrollado como una aplicación informática que se integrará en el sistema agroecológico de ayuda a la decisión MicroLEIS DSS. CarboSOIL, diseñado como una herramienta geográfica en un entorno SIG para el análisis espacial de las entradas y salidas del modelo, ha demostrado su capacidad para cuantificar y comprender la distribución de carbono en el suelo.

Carbono orgánico del suelo en escenarios de cambio climático

El cambio climático que se espera en los próximos va a tener un impacto negativo sobre el contenido de COS en las capas superiores de la sección del suelo (0-25 y 25-50 cm). Los mayores descensos en COS se predicen en el escenario medio-alto de emisiones A2. En concreto, las áreas que se verán afectadas en mayor medida son las zonas sensibles como las marismas y los cultivos de árboles frutales. Entre los distintos tipos de suelo estudiados, los Regosoles bajo espacios abiertos o en áreas con poca cobertura vegetal se verán especialmente afectados.

El trabajo desarrollado en esta tesis podría ser de utilidad para apoyar la toma de decisiones en la gestión del territorio y ayudar a diseñar estrategias de adaptación al cambio climático de las regiones mediterráneas. La metodología desarrollada en esta investigación es fácilmente extrapolable a otras zonas mediterráneas que dispongan de datos climáticos, de suelos, del territorio y del uso del suelo. En esta tesis, se considera un espacio temporal de 51 años para el análisis de los cambios de uso del suelo, representativo de periodos a largo plazo, sin embargo, estudios adicionales que impliquen períodos más cortos serían de gran ayuda para un mejor conocimiento de la dinámica terrestre del carbono. En las predicciones futuras de COS en escenarios de cambio global, el uso del suelo no ha sido modificado, ya que el propósito de este estudio ha sido el de evaluar los cambios en las existencias de COS en respuesta al cambio climático. Sin embargo, se esperan considerables cambios del uso del suelo en las próximas décadas, por lo que sería de gran interés el estudio del futuro impacto que estos cambios podrían tener en las reservas de carbono en los suelos.

REFERENCES

Albadalejo J, Martínez-Mena M, García Franco N, Almagro M, Ortiz Silla R (2011) Sensibilidad del carbono orgánico del suelo al cambio global: influencia de la profundidad. In: Ortiz Silla A, Sánchez Navarro A (Eds.). Control de la degradación y uso sostenible del suelo. pp. 577-580. University of Murcia, Murcia

Álvaro-Fuentes J, Paustian, K (2011) Potential soil carbon sequestration in a semiarid Mediterranean agroecosystem under climate change: Quantifying management and climate effects. Plant Soil 338: 261-272

Álvaro-Fuentes J, Easter M, Paustian, K (2012) Climate change effects on organic carbon storage in agricultural soils of northeastern Spain Agriculture, Ecosystems and Environment 155: 87-94

Anaya-Romero M, Pino R, Moreira JM, Muñoz-Rojas M, De la Rosa D (2011) Analysis of soil capability versus land use change by using CORINE land cover and MicroLEIS. International Agrophysics 25(4): 395-398

Anaya-Romero A, Muñoz-Rojas M, Pino R, Jordán A, Zavala LM, de la Rosa D (2012) Carbosoil, a land evaluation model for soil carbon accounting. Geophysical Research Abstracts 14: EGU2012-7227

Andrén O and Kattere T (1997) ICBM: the introductory carbon balance model for exploration of soil carbon balances. Ecological applications 7: 1226-36

Andres C, Ojeda F (2002) Effects of afforestation with pines on woody plant diversity of Mediterranean heathlands in Southern Spain. Biodiversity and Conservation 11:1511-1520

Arrouays D, Deslais W, Badeau V (2001)The carbon content of topsoil and its geographical distribution in France. Soil Use and Management 17: 7-11

Bahn M, Kutsch WL, Heinemeyer A (2009) Synthesis: emerging issues and challenges for an integrated understanding of soil carbon fluxes. In: Kutsch WL, Bahn M, Heinemeyer A. pp. 257-271. Cambridge. Universty Press Cambridge

Batjes NH (1996). Total carbon and nitrogen in the soils of the world, European Journal of Soil Sciences 47: 151-163

Batjes NH (2002) Carbon and nitrogen stocks in the soils of Central and Eastern Europe, Soil Use and Management 18: 324-329

Batjes NH (2005) Organic carbon stocks in the soils of Brazil, Soil Use and Management 21: 22-24

Batjes NH, Dijkshoorn JA (1999) Carbon and nitrogen stocks in the soils of Amazon Region. Geoderma 89: 273-286

Bellamy PH, Loveland PJ, Bradley RI, Lark RM, Kirk GJD (2005) C losses from all soils across England and Wales 1978-2003. Nature 437: 245-248

Bermejo D, Cáceres F, Moreira JM, Montes JE, Sánchez S, Laguna D, Caballo A, Anaya-Romero M, Asensio B (2011) Medio siglo de cambios en la evolución de usos del suelo en Andalucía 1956-2007. Consejería de Medio Ambiente. Junta de Andalucía: Sevilla

Berthelot M, Friedlingstein P, Ciais P, Dufresne JL, Monfray P. How uncertainties in future climate change predictions translate into future terrestrial carbon fluxes (2005) Global Change Biololgy 11:959-970

Bierke A, Kaiser K, Guggenberger G (2008) Crop residue management effects on organic matter in paddy soils. The lignin component. Geoderma 146: 48-57

Blake GR, Hartge KH (1986) Bulk density. In: Methods of Soil Analysis-Part 1, Physical and Mineralogical Methods, 2nd edn. Klute A. (ed.). American Society of Agronomy, Madison

Blondel J, Aronson J (1995) Biodiversity and ecosystem function in the Mediterranean basin: human and non-human determinants. In: Davis G.W., Richardson D.M., (Eds). Mediterranean-Type Ecosystems. pp. 42-20. Springer. New York

Boix-Fayos C, de Vente J, Albaladejo J, Martínez-Mena M (2009) Soil carbon erosion and stock as affected by land use changes at the catchment scale in Mediterranean ecosystems, Agriculture, Ecosystems and Environment 133: 75-85

Bolliger J, Hagedorn F, Leifeld J, Böhl J, Zimmermann S, Soliva R, Kienast F (2008) Effects of land-use change on carbon stocks in Switzerland. Ecosystems 11: 895-907

Bouma J, Varallyay G, Batjes NH (1998) Principal land use changes anticipated in Europe. Agriculture Ecosystems and Environment 67:103-119

Box GP, Cox DR (1964) An analysis of transformations. Journal of the Royal Statistical Society, Series B 26 (2): 211-252

Bradley RI, Milne R, Bell J, Lilly A, Jordan C, Higgins A (2005) A soil carbon and land use database for the United Kingdom, Soil Use and Management 21: 363-369

Brahim N, Bernoux M, Blavet D, Gallali T (2010) Tunisian soil organic carbon stocks. International Journal of Soil Sciences 5: 34-40

Breiman L (2001) Random forests. Machine Learning 45: 5-32

Cantarello E, Newton A, Hill RA (2010) Potential effects of future land-use change on regional carbon stocks in the UK . Environmental Science & Policy 14:40-52

Caraveli H (2000) A comparative analysis on intensification and extensification in Mediterranean agriculture: Dilemmas for LFA's policy. Journal of Rural Studies 16:231-242

Cerdà A, Lavee H, Romero-Díaz A, Hooke J, Montanarella L (2010) Preface. Land Degradation and Development 21: 71-74

Chen C, Xu Z, Mathers N (2004) Soil C pools in adjacent natural and plantation forests of subtropical Australia. Soil Science Society of America Journal 68: 282-291

Chertov OG, Komarov AS, Nadporozhskaya M, Bykhovets SS and Zudin SL (2001) ROMUL – a model of forest soil organic matter dynamics as a substantial tool for forest ecosystem modelling. Ecological Modelling 138: 289-308

Chiesi M, Moriondo M, Maselli F, Gardin L, Fibbi L, Bindi M, Running SW (2010) Simulation of Mediterranean forest carbon pools under expected environmental scenarios. Canadian Journal of Forest Research 40(5):850-860

Christensen OB, Goodess CM, Harris I, Watkiss P (2011) European and Global Climate Change Projections: Discussion of Climate Change Model Outputs, Scenarios and Uncertainty in the EC RTD ClimateCost Project. In: Watkiss, P, editor. The ClimateCost Project. Final Report. Volume 1: Europe. Sweden: Stockholm Environment Institute

Ciais P, Schelhaas MJ, Zaehle S, Piao SL, Cescatti A, Liski J, Luyssaert S, Le-Maire G, Schulze E-D, Bouriaud O, Freibauer A, Valentini R, Nabuurs GJ (2008) Carbon accumulation in European forests. Nature Geoscience 1:425–429

Coleman K. and Jenkinson DS (1995) RothC-26. 3. A model for the turnover of carbon in soil: model description and user guide. ISBN 0951 446 96.

Coleman K. and DS Jenkinson (1996) RothC-26.3 –A model for the turnover of carbon in soil. NATO ASI Series,Vol. 138. Evaluation of Soil Organic Matter Models. Eds. D. S. Powlson, P. Smith and J.U. Smith

Coleman K, Jenkinson DS. ROTHC-26.3 (1999) A model for the turnover of carbon in soil. In: Powlson DS, Smith P, Smith JU, editors. Evaluation of soil organic matter models using existing, long-term datasets. Heidelberg: NATO ASI Series I, Vol. 38, Springer-Verlag p. 237-246

Cruickshank MM, Tomlinson RW, Trew S (2000) Application of CORINE land-cover mapping to estimate carbon stored in the vegetation of Ireland. Journal of Environmental Management 58: 269-287

CSIC-IARA (1989) Mapa de suelos de Andalucía, Instituto Andaluz de la Reforma Agraria (Junta de Andalucía), Sevilla. Consejo Superior de Investigaciones Científicas, Madrid

Cutler DR, Edwards TC, Beard KH, Cutler A, Hess KT, Gibson J, Lawler JJ (2007) Random forests for classification in Ecology. Ecology 88 (11): 2783-2792

Dai W, Huang Y (2006) Relation of soil organic matter concentration to climate and altitude in zonal soils of China. Catena 65: 87-94

Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440: 165-173

Dawson JJC, Smith P (2007) C losses from soil and its consequences for land-use management. Science of the Total Environment 382: 165-190De la Rosa D, Mayol F, Moreno F, Cabrera F, Diaz-Pereira E, Fernández J. A Land Evaluation Decision support System (MicroLEIS DSS) for Agricultural Soil Protection. Environmental Modelling and Software 19: 929-942

De la Rosa D (1984) Catálogo de Suelos de Andalucía. Agencia de Medio Ambiente. Junta de Andalucía.

De la Rosa D (2008) Evaluación agro-ecológica de suelos para el desarrollo sostenible. Ed. Mundi-Prensa Libros, Madrid.

De la Rosa D, Mayol F, Moreno F, Cabrera F, Diaz-Pereira E, Antoine J (2002) A multilingual soil profile database (SDBm Plus) as an essential part of land resources information systems. Environmental Modelling and Software 17: 721-730

De la Rosa D, Mayol F, Moreno F, Cabrera F, Diaz-Pereira E, Fernández M, De la Rosa D Jr (2004) A Land Evaluation Decision support System (MicroLEIS DSS) for Agricultural Soil Protection, Environmental Modelling and Software 19: 929-942

De la Rosa D, Anaya-Romero M, Diaz-Pereira E, Heredia N, Shahbazi F (2009) Soil-specific agro-ecological strategies for sustainable land use A case study by using MicroLEIS DSS in Sevilla Province (Spain). Land Use Policy 26:1055-1065

De Vries W, Reinds GJ, Posch M, Sanz M, Krause G, Calatyud V, Dupouey J, Sterba H, Gundersen P, Voogd J, Vel E (2003) Intensive Monitoring of Forest Ecosystems in Europe. Tech. Rep., EC. UN/ECE: Brussels

Díaz-Hernández JL, Barahona Fernádez E, Linares González J (2003) Organic and inorganic carbon in soils of semiarid regions: a case study from the Guadix–Baza basin (Southeast Spain), Geoderma 114: 65-80

Eaton J, McGoff N, Byrne KA, Leahy P, Kiely G (2008) Land cover change and soil OCarbon stocks in the Republic of Ire land 1851-2000. Climatic Change 91:317-334

Eom SB, Le SM, Kim EB, Somarajan C (1998) A Survey of Decision Support System Applications. Journal of Operational Research 49: 109-120

Erb K-H (2004) Land-use related changes in aboveground carbon stocks of Austria's terrestrial ecosystems. Ecosystems 7: 563-572

ESRI (2006) ArcGIS 9.2. Redlands, CA: Environmental Scientific Research Institute

ESRI (2011) ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute

Eswaran H, Van der Berg E, Reich P (1993) Organic carbon in soils of the world, Soil Science Society of America Journal 57: 192-194.

Eswaran H, Reich PF, Kimble JM, Beinroth FH, Padmanabhan E, Moncharoen P (2000) Global carbon stocks. In: Lal R, Kimble JM, Eswaran H, Stewart BA, editors. Global climate change and pedogenic carbonates. Boca Raton, FL: Lewis

Eswaran H, Van den Berg E, Reich P, Kimble J (2003) Global Soil C Resources, in: Lal R, Kimble J, Levine E, Stewart BA. (Eds.), Soils and Global Change CRC Lewis Publishers: Boca Raton, FL, pp. 27-43

Falloon P, Smith P (2003) Accounting for changes in soil carbon under the Kyoto Protocol: need for improved long-term data sets to reduce uncertainty in model projections. Soil Use and Management 19: 265-269

Falloon PD, Smith P, Smith JU, Szabó J, Coleman K, Marshall S (1998) Regional estimates of carbon sequestration potential: linking the Rothamsted Carbon Model to GIS databases. Biology and Fertility of Soils 27: 236-241.

Falloon P, Smith P, Szabó J and Pásztor L (2002) Comparison of approaches for estimating carbon sequestration at the regional scale. Soil Use and Management 18: 164-174

Fantappiè M, L'Abate G, Costantini EAC (2011) The influence of Climate Change on the Soil Organic Carbon Content in Italy from 1979 to 2008. Geomorphology 135: 343-352

FAO (2006) Guidelines for soil description, 4th edition, Food and Agriculture Organization of the United Nations, Rome

Farley KA, Kelly EF, Hofstede RGM (2004) Soil organic C and water retention after conversion of grasslands to pine plantations in the Ecuadorian Andes. Ecosystems 7: 729-739

Fayyad G, Shapiro P, Smyth P (1996) From data mining to knowledge discovery in databases. AI Magazine, 17(3): 37-54

Feranec J, Jaffrain G, Soukup T, Hazeu G (2010) Determining changes and flows in European landscapes 1990-2000 using CORINE land cover data. Applied Geography 30: 19-35

Fitter A, Elmqvist T, Haines-Young R, Potschin M, Rinaldo A, Setala H, Stoll-Kleemann S, Zobel M , Murlis J (2010) An Assessment of Ecosystem services and biodiversity in Europe. Issues in Environmental Science and Technology 30: 1-28

Flores MV, Ferrer F, Jiménez G, Valera A, Goberna M (2007) Distribución del contenido de carbono orgánico en los suelos del norte de Castellón. In: Rodríguez Rodríguez A., Arbeló C.D., (Eds), Control de la degradación de suelos y la desertificación. pp. 207-208, University of La Laguna, La Laguna

Freibauer A, Rounsevell MDA, Smith P, Verhagen J (2004) Carbon sequestration in the agricultural soils of Europe. Geoderma 122: 1-23

Gamboa AM, Galicia L (2011) Differential influence of land use/cover change on topsoil C and microbial activity in low-latitude temperate forests. Agriculture, Ecosystems and Environment 142 (3-4): 280-290

Ganuza A, Almendros G (2003) Organic carbon storage in soils of representative ecosystems in the Basque Country (Northern Spain) as related to climate, vegetation type and edaphic variables, Biology and Fertility of Soils 37: 154-162

García M, Riaño D, Chuvieco E, Danson FM (2010) Estimating biomass carbon stocks for a mediterranean forest in central spain using LiDAR height and intensity data. Remote Sensing of Environment 114: 816-830

Gibbs, HK, S Brown, JO Niles, and JA Foley (2007) Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters 2:045023 (13 p)

Gibson TS, Chan KY, Sharma G, Shearman R (2002) Soil carbon sequestration utilising recycled organics. A review of the scientific literature, Project 00/01R-3.2.6A.2002, Organic Waste Recycling Unit, NSW Agriculture, NSW Agriculture, Sydney

Gibert K, Sànchez-Marrè, Codina V (2010) Choosing the right data mining technique: classification of methods and intelligent recommenders. In Proc. of the iEMSs Fifth Biennial Meeting: Int'l Congress on Environmental Modelling and Software 1: 2448-2453.

Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. Global and Planetary Change 63: 90-104

Goodale CL, Apps MJ, Birdsey RA., Field CB, Heath LS., Houghton RA, Jenkins JC., Kohlmaier GH, Kurz W, Liu S, Nabuurs GL, Nilsson S, Shvidenko AZ (2002) Forest carbon sinks in the northern hemisphere. Ecological Applications 12:891-899

González-Pérez J, González-Vila FJ, Almendros G, Knicker H (2004) The effect of fire on soil organic matter – a review, Environment International 30: 855-870

Graham MH (2003) Confronting multicollinearity in ecological multiple regression. Ecology 84: 2809-2815

Grimm R, Behrens T, Märker M, Elsenbeer H. (2008) Soil organic carbon concentrations and stocks on Barro Colorado Island - Digital soil mapping using RandomForests analysis. Geoderma 146: 102-113

Grüneberg E, Schöning I, Kalko EKV, Weisser WW (2010) Regional organic carbon stock variability: A comparison between depth increments and soil horizons. Geoderma 155: 426-433

Guo LB, Gifford RM (2002) Soil C stocks and land use change: a meta analysis. Global Change Biololgy 8: 345-360

Guo L, Falloon P, Coleman K, Zhou B, Li Y, Lin E. and Zhang F (2007) Application of the RothC model to the results of long-term experiments on typical upland soils in northern China. Soil Use and Management 23: 63-70

Hashimoto S, Ugawa S, Morisada K, Wattenbach M, Smith P and Matsuura Y (2012) Potential carbon stock in Japanese forest soils - simulated impact of forest management and climate change using the CENTURY model. Soil Use and Management 28: 45-53

Hastie T, Tibshirani R, Friedman J (2001) The Elements of Statistical Learning: Data Mining, Inference and Prediction, Springer Series in Statistics, Springer Verlag, New York

Herold M (2006) A joint initiative for harmonization and validation of land cover datasets. IEEE Transactions on Geoscience and Remote Sensing 44: 1719-1727

Heymann Y, Steenmans Ch, Croissille G, Bossard M (1994) Corine Land Cove Technical Guide. Luxembourg: Office for Official Publications of the European Communities

Hontoria C, Rodríguez-Murillo JC, Saa A (1999) Relationships between soil organic carbon and site characteristics in peninsular Spain, Soil Science Society of America Journal 63: 617-621

Houghton RA, Boone RD, Melillo JM, Palm CA, Woodwell GM, Myers N, Moore B, Skole DL (1985) Net flux of carbon dioxide from tropical forest in 1980. Nature 316: 617-620

Houghton RA, Hackler JL (1999) Emissions of carbon from forestry and land-use change in tropical Asia. Global Change Biology 5: 481-492

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (2001) Climate change 2001: the scientific basis. Cambridge: Cambridge University Press

Houghton RA (2005) The contemporary carbon cycle. In: Schlesinger, W.H. (Ed.) Biogeochemistry, pp. 473-513, Elsevier-Pergamon, Oxford

Howard PJA, Loveland PJ, Bradley RI, Dry FT, Howard DM, Howard DC (1995) The carbon content of soil and its geographical distribution in Great Britain, Soil Use and Management 11: 9-15

Ibáñez JJ, Sánchez J, de Alba S, López M, Boixadera J (2005) Collection of soil information in Spain: a review. In: Jones R.J.A., Houskova B., Bullock P., Montanarella L., (Eds), Soil resources of Europe: 2nd ESB Research Report No. 9. Luxembourg: Office for Official Publications of the European Communities

ICA (1999) Modelo Digital de Elevaciones. 100 m. CD-ROM. Sevilla: Instituto de Cartografía de Andalucía. Consejería de Obras Públicas y Transportes (Junta de Andalucía)

IPCC (2000) Special report on emissions scenarios—a special report of working group III of the Intergovernmental Panel on Climate Change. Cambridge:Cambridge University Press

IPCC (2007) Climate Change 2007: The Physical Science Basis. Cambridge/New York: Cambridge University Press

IUSS Working Group WRB (2006) World reference base for soil resources 2006. World Soil Resources Reports No 103, Food and Agriculture Organization of the United Nations, Rome.

Izaurralde RC, Williams JR, McGill WB, Rosenberg N.J., Quiroga Jakas MC (2006) Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological. Modelling 192: 362-384

Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritz Hagedorn F, Johnson DW, Minkkinen K, Byrne KA (2007) How strongly can forest management influence soil C sequestration? Geoderma 137: 253-268

Jandl R, Rodeghiero M, Olsson M (2011) Soil Carbon in Sensitive European Ecosystems: From Science to Land Management. From Science to Land Management. COST Wiley-Blackwell, Hoboken: 296

Janssen R, Goosena H, Verhoevenb ML, Verhoevenb JTA, Omtzigta AQA and Maltby E (2005) Decision support for integrated wetland management. Environmental Modelling and Software 30: 215-229

Janssens IA, Freibauer A, Schlamadinger B, Ceuleman R, Ciai P, Dolman AJ, Heimann M, Nabuurs GJ, Smith P, Valentini R and Schulze ED (2005) The carbon budget of terrestrial ecosystems at country scale – a European case study. Biogeosciences 2:15-26

Jenny H (1941) Factors of soil formation: a system of quantitative pedology, Mc Graw-Hill. London

Jobbagy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications 10: 423-436

Johnson MG, Kern JS (2002) Quantifying the Carbon held in forested soils of the United States and Puerto Rico. In: Kimble JM, Heath LS, Birdsey RA, Lal R, editors. The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effects. Boca Raton, FL: Lewis Publishers

Jones RJA, Hiederer R, Rusco E, Loveland PJ and Montanarella L (2004) The map of organic carbon in topsoils in Europe, Version 1.2, September 2003: Explanation of Special Publication Ispra 2004 No.72 (S.P.I.04.72). European Soil Bureau Research Report No.17, EUR 21209 EN, 26pp. and 1 map in ISO B1 format. Office for Official Publications of the European Communities, Luxembourg.

Jones C, McConnell C, Coleman K, Cox P, Falloon P, Jenkinson D and Powlson D (2005) Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil. Global Change Biology 11: 154-166

Jordán A, Zavala L M, Bellinfante N (2007) Reserva de Carbono en Suelos Forestales Mediterráneos. In: Bellinfante N, Jordán A, (Eds), Tendencias Actuales de la Ciencia del Suelo, Universidad de Sevilla, pp. 638-647

Jordán A, Zavala LM (2009) Obtención de Indicadores a partir de la Base de Perfiles de Suelo para su aplicación a la Modelización Climática. Unpublished technical report. Sevilla: Consejería de Medio Ambiente. Junta de Andalucía;

Kapos V, Ravilious C, Campbell A, Dickson B, Gibbs HK, Hansen MC, Lysenko I, Miles L, Price J, Scharlemann JPW, Trumper KC (2008) Carbon and biodiversity: a demonstration atlas. United Nations Environment Programme World Conservation Monitoring Centre, UNEP-WCMC, Cambridge, UK

Kauppi PE, Mielikäinen K, Kuusela K (1992) Biomass and carbon budget of European forests, 1971–1990. Science 256: 70-74

Kauppi PE, Rautiainen A, Korhonen KT, Lehtonen AC, Liski J, Nöjd P, Tuominen S, Haakana M, Virtanen T (2010) Changing stock of biomass carbon in a boreal forest over 93 years. Forest Ecology and Management 259: 1239-1244

Kirschbaum MUF (2000) Will changes in soil organic matter act as a positive or negative feedback on global warming? Biogeochemistry 48: 21-51

Kutílek M (2011) Soils and climate change. Soil and Tillage Research 117: 1-7

Kutsch WL, Bahn M, Heinemeyer A (2009) Soil carbon relations: an overview. In: Soil Carbon Dynamics: An Integrated Methodology (Eds Kutsch WL, Bahn M, Heinemeyer A), Cambridge University Press, Cambridge, 1–15

Lal P, Kimble JM, Follett RF, Stewart BA (2001) Assessment Methods for Soil Carbon. Boca Raton, FL: Lewis

Lal R (2003) Global potential of soil C sequestration to mitigate the greenhouse effect, Critical Reviews in Plant Sciences 22: 151-184

Lal R (2004) Soil carbon sequestration to mitigate climate change. Geoderma 4: 123: 1-22

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, George PS, Homewood K, Imbernon J, Leemans R, Li X, Moran EF, Mortimore M, Ramakrishnan PS, Richards JF, Skanes H, Steffen W, Stone GD, Svedin U, Veldkamp TA, Vogel C, Xu J (2001) The causes of land-use and land-cover change: moving beyond myths. Global Environmental Change 11: 261-269

Lambin EF, Geist HJ (2006) Land use and land cover change. Local processes and global impacts, Global Change - The IGBP Series, ed. Springer Verlag: Berlin, Heidelberg

Lantz A, Lal R, Kimble J (2001) Land use effects on soil C pools in two major land resource areas of Ohio, USA, in: Stott DE, Mohtar RH, Steinhardt GC. (Eds.), Sustaining the global farm. Selected papers from the 10th International Soils Conservation Organization meeting, May 1999. Purdue University, pp. 499-502

Leifeld J, Bassin S, Fuhrer J (2005) Carbon stocks in Swiss agricultural soils predicted by land-use, soil characteristics, and altitude. Agriculture Ecosystems and Environment 105: 255-266

Lettens S, Van Orshoven J, Van Wesemael B, De Vos B, Muys B (2005) Stocks and fluxes of soil organic carbon for landscape units in Belgium derived from heterogeneous data sets for 1990 and 2000. Geoderma 127: 11-23

Li CS, Frolking S and Harriss R (1994) Modeling carbon biogeochemistry in agricultural soils. Global Biogeochemical Cycles 8: 237-54

Liebens J, VanMolle M (2003) Influence of estimation procedure on soil organic carbon stock assessment in Flanders, Belgium, Soil Use and Management, 19, 364-371

Liski J, Perruchoud D, Karjalainen T (2002) Increasing carbon stocks in the forest soils of western EUROPE. Forest Ecology and Management 169: 159-175

Liski J, Palosuo T, Peltoniemi M, Sievänen R (2005) Carbon and decomposition model Yasso for forest soils. Ecological Modelling 189: 168-182

Liski J, Lehtonen A, Palosuo T, Peltoniemi M, Eggers T, Muukkonen P, Mäkipää R (2006) Carbon accumulation in Finland's forests 1922-2004-an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil. Annals of Forest Science 63: 687-697

Lokupitiya E, Paustian K (2006) Agricultural soil greenhouse gas emissions: a review of national Inventory Methods. Journal of Environmental Quality 35: 1413-1427

Lorena AC, Jacintho LFO, Siqueira MF, De Giovanni R, Lohmann LG (2011) Comparing machine learning classifiers in potential distribution modeling. Expert Systems with Applications 38: 5268-5275

Lucht W, Schaphoff S, Erbrecht T, Heyder U, Cramer W (2006) Terrestrial vegetation redistribution and carbon balance under climate change. Carbon Balance and Management I: 1-7

Lugato E, Berti A (2008) Potential carbon sequestration in a cultivated soil under different climate change scenarios: A modelling approach for valuating promising management practices in north-east Italy. Agriculture, Ecosystems and Environment 128: 97-103

Macías F, Calvo de Anta R, Rodríguez Lado L, Verde R, Pena Pérez X, Camps Arbestain M (2004) El sumidero de carbono de los suelos de Galicia. Edafología 11: 341-376

Maestre FT, Cortina J, Bautista S, Bellot J (2003) Does Pinus halepensis facilitate the establishment of shrubs under semi-arid climate. Forest Ecology and Management: 176: 147-160

Marland G, Garten CT, Post WM, West TO (2004) Studies on enhancing C sequestration in soils. Energy 29: 1643-1650

Martin MP, Wattenbach M, Smith P, Meersmans J, Jolivet C, Boulonne L, Arrouays D (2011) Spatial distribution of soil organic carbon Stocks in France. Biogeosciences 8: 1053-1065

Meersmans J, De Ridder F, Canters F, De Baets S, Van Molle M (2008) A multiple regression approach to assess the spatial distribution of soil organic carbon (SOC) at the regional scale (Flanders, Belgium). Geoderma 143: 1-13

Millán MM, Estrela MJ, Miró J (2005) Rainfall components: variability and spatial distribution in a Mediterranean Area (Valencia Region) J. Clim. 18: 2682-2705

Milne R, Brown TA (1997) Carbon in the vegetation and soils of Great Britain. Journal of Environmental Management 49: 413-433

Mitchell TD, Carter TR, Jones PD, Hulme M, New M (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). Working Paper 55. Norwich: Tyndall Centre for Climate Change Research, University of East Anglia

Mol Dijkstra JP, Reinds GJ, Kros H, Berg B, de Vries W (2009) Modelling soil carbon sequestration of intensively monitored forest plots in Europe by three different approaches. Forest Ecology and Management 258: 1780-1793

Mollicone D, Achard F, Federici S, Eva H, Grassi G, Belward A, Raes F, Seufert G, Stibig H, Matteucci G, and Schulze E (2007) An incentive mechanism for reducing emissions from conversion of intact and non-intact forests. Climatic Change 83: 477-493

Mondini C, Coleman K, Whitmore AP (2012) Spatially explicit modelling of changes in soil organic C in agricultural soils in Italy, 2001–2100: Potential for compost amendment. Agriculture, Ecosystems & Environment 153: 24-32

Monge G, Rodríguez AJ, Rodríguez JA, Anaya-Romero M, de la Rosa, D (2008) Generación de mapas lito-edafológicos de Andalucía. MAPPING. Revista Internacional de Ciencias de la Tierra 124: 38-49

Montiel-Molina C (2006) The Restoration of Forest Landscapes through Farmland Afforestation. In: Agnoletti editor. The conservation of cultural landscapes. Wallingford, UK: CABI

Moreira JM (2007) Mapas de usos y coberturas vegetales del suelo de Andalucía. Escala 1/25000. Guía Técnica. Consejería de Medio Ambiente, Junta de Andalucía. Sevilla, Spain

Morisada K, Ono K, Kanomata H (2004) Organic carbon stock in forest soils in Japan. Geoderma 119: 21-32

Mueller T, Jensen LS, Hansen S and Nielsen NE (1996). Simulating soil carbon and nitrogen dynamics with the soil–plant–atmosphere system model Daisy. In: D.S. Powlson, P. Smith and J.U. Smith, Editors, Evaluation of Soil Organic Matter Models Using Existing Long-Term Datasets. NATO ASI Series I vol. 38, Springer-Verlag, Heidelberg, pp. 275–282

Muñoz-Rojas M, De la Rosa D, Zavala LM, Jordan A, Anaya-Romero M (2011) Changes in land cover and vegetation carbon stocks in Andalusia, Southern Spain (1956-2007), Science of the Total Environment 409: 2796-2806

Muñoz-Rojas M, Jordán A, Zavala LM, De la Rosa D, Abd-Elmabod SK, Anaya-Romero M (2012) Organic carbon stocks in Mediterranean soil types under different land uses (Southern Spain). Solid Earth Discussions 4: 1-34

Nabuurs G-J, Schelhaas M-J, Mohren GMJ, Field CB (2003) Temporal evolution of the European forest sector carbon sink from 1950 to 1999. Global Change Biology 9: 152-160

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner HH, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) IPCC Special Report on Emissions Scenarios. Cambridge and New York: Cambridge University Press; 599pp

Neufeldt H (2005) Carbon stocks and sequestration potentials of agricultural soils in the federal state of Baden-Württemberg, SW Germany Journal of Plant Nutrition and Soil Science 168: 202–211

Neumann K, Herold M, Hartley A, Schmullius C (2007) Comparative assessment of CORINE2000 and GLC2000: Spatial analysis of land cover data for Europe. International Journal of Applied Earth Observation and Geoinformation 9: 425-437

Novara A, Gristina L, Bodì MB, Cerdà,A (2011) The impact of fire on redistribution of soil organic matter on a Mediterranean hillslope under maquia vegetation type. Land Degradation and Development 22: 530-536

Novara A, La Mantia T, Barbera V, Gristina L (2012). Paired-site approach for studying soil organic carbón dynamics in a Mediterranean semiarid Environment. Catena 89: 1-7

Oades JM (1988) The retention of organic matter in soils. Biogeochemistry 5: 35-70

Ogle SM, Paustian K (2005) Soil organic carbon as an indicator of environmental quality at the national scale: inventory monitoring methods and policy relevance. Canadian Journal of Soil Science 85: 531–540

Oliet Palá JM, Agudo Romero R, Muñoz Martínez M, del Pino del Castillo O (2007) Primer inventario de sumideros de CO_2 en Andalucía. Consejería de Medio Ambiente (Junta de Andalucía). Sevilla

Oliveira S, Oehler F, San-Miguel-Ayanz J,Camia A , Pereira JMC (2012) Modeling spatial patterns of fire occurrence in Mediterranean Europe using Multiple Regression and Random Forest. Forest Ecology and Management 275: 117–129

Ostle NJ, Levy PB, Evans CD, Smith P (2009) UK land use and soil carbon sequestration. Land Use Policy 26: 274-283

Padilla FM, Vidal B, Sánchez J, Pugnaire FI (2010) Land use changes and carbon sequestration through the twentieth century in a Mediterranean mountain ecosystem:Implications for land management. Journal of Environmental Management 91: 2688-2695

Pardos JA (2010) Los ecosistemas forestales y el secuestro de carbono ante el calentamiento global. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria; Madrid

Parton WJ, Schimel DS, Cole CV, Ojima DS (1987) Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal 51: 1173-1179

Parton WJ, Stewart JWB, and Cole CV (1988) Dynamics of C, N, P and S in grassland soils. a model. Biogeochemistry 5: 109-131

Parton WJ, McKeown R, Kirchner V, Ojima D (1992) CENTURY Users' Manual. Fort Collins: Natural Resource Ecology Laboratory, Colorado State University

Paul KI, Polglase PJ, Nyakuengama JG, Khanna PK (2002) Change in soil C following afforestation. Forest Ecology and Management 168: 241-257

Paustian K (2002) Organic matter and global cycle. In: Lal R., (Ed), Encyclopedia of Soil Science, pp 895-898, Marcel Dekker Inc, NY

Paustian K, Elliott ET, Killian K (1997) Modeling soil carbon in relation to management and climate change in some agroecosystems in central North America. In: Lal R, Kimble JM, Follett RF and Stewart BA, editors. Soil Processes and the Carbon Cycle. Boca Raton, FL, USA: CRC Press; p. 459-471

Pedhazur E J (1997) Multiple regression in behavioral research: Explanation and prediction (3rd ed.). New York: Harcourt Brace.

Peñarrocha D (1994) Precipitaciones: volúmenes y distribución espacial. In: Pérez Cueva, A. (Eds.), Atlas Climático de la Comunidad Valenciana (1961–1990). Consellería d'Obres Públiques, Urbanisme i Transports, Generalitat Valenciana, Valencia, pp. 86–89

Pereira TC, Seabra T, Maciel H, Torres P (2009) Portuguese National Inventory Report on Greenhouse Gases, 1990-2007 Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Amadora: Portuguese Environmental Agency

Phachomphon K, Dlamini P, Chaplot V (2010) Estimating carbon stocks at regional level using soil information and easily accessible auxiliary variables. Geoderma 155: 372-380

Pino R, Anaya-Romero M, Cubiles de la Vega MD, Pascual Acosta A, Jordán López A, Bellinfante Crocci N (2010) Predicting the potential habitat of oaks with data mining models and the R system. Environmental Modelling & Software 25: 826-836

Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. Global Change Biology 6: 317-327

Post WM, Izaurralde RC, Mann LK and Bliss N (1999) Monitoring and verifying soil organic carbon sequestration. pp. 41-66. In: (N. Rosenberg, R.C. Izaurralde, and E. L. Malone, eds.) Carbon Sequestration in Soils: Science, Monitoring, and Beyond. Proceeding of the St. Michaels Workshop, December 1998. Battelle Press.

Powlson DS, Whitmore AP, Goulding KWT (2011) Soil C sequestration to mitigate climate change: a critical re-examination to identify the true and the false. European Journal of Soil Science 62: 42-55

Ramankutty N, Foley JA, Olejniczak, NJ (2002) People on the land: changes in global population and croplands during the 20th century. Ambio 31: 251-257

Ravindranath NH, Ostwald M (2008) Carbon Inventory Method. Springer Publishers.pp. 121- 154.

Rodeghiero M, Tonolli S, Vescovo L, Gianelle D, Cescatti A, Sottocornola M (2010) INFOCARB: a regional scale forest carbon inventory (Provincia Autonoma di Trento, Southern Italian Alps), Forest Ecology and Management 259: 1093-1101

Rodríguez-Murillo JC (2001) Organic carbon content under different types of land use and soil in peninsular Spain. Biology and Fertility of Soils 33: 53-61

Roig S, Rubio A (2009) El sistema agroforestal dehesa como sumidero de C: hacia un modelo conjunto de la vegetación y el suelo. 5º Congreso Forestal Español: Ávila, España, Sept 21-25 (http://www.ecogesfor.org/publicaciones.html).

Romanya J, Rovira P, Duguy B, Vallejo R, Rubio A (2007) C sequestration issues in the Mediterranean soils, in: Jandl, R., Olsson, M., (Eds.), COST Action 639 Greenhouse- gas budget of soils under changing climate and land use (burn-out): Vienna, pp.15-22.

Ruiz-Navarro A, Barberá GG, Navarro-Cano JA, Albaladejo J, Castillo VM (2009) Soil dynamics in Pinus halepensis reforestation: effect of microenvironments and previous land use. Geoderma 2009;153:353-361.

Ruiz Sinoga JD, Pariente S, Romero Diaz A, Martinez Murillo JF (2012) Variability of relationships between soil organic carbon and some soil properties in Mediterranean rangelands under different climatic conditions (South of Spain). Catena 94: 17-25

Salome C, Nunan N, Pouteau V, Lerch TZ, Chenu C (2010) Carbon dynamics in topsoil and in subsoil may be controlated by different regulatory mechanisms. Global Change Biology 16: 416-426

Sauter VL (1997) Decision support systems: an applied managerial approach. New York: John Wiley; 432 pp

Serra P, Pons X, Sauri D (2008) Land-cover and land-use change in a Mediterranean landscape: a spatial analysis of driving forces integrating biophysical and human factors. Applied Geography 28: 189-209

Schöning I, Totsche KU, Kögel-Knabner I (2006) Small scale spatial variability of organic carbon stocks in litter and solum of a forested Luvisol, Geoderma 136: 631-642

Scott NA, Tate KR, Giltrap DJ, Tattersall Smith C, Wilde HR, Newsome PJF, Davis MR (2002) Monitoring land-use change effects on soil C in New Zealand: quantifying baseline soil C stocks. Environmental Pollution 116: 167-186

Schrumpf M, Schumacher J, Schöning I, Schulze ED (2008) Monitoring carbon stock changes in European soils: process understanding and sampling strategies. In: Dolman A.J., Freibauer A., Valentini R., (Eds). The Continental-Scale Greenhouse Gas Balance of Europe. Springer, NY

Schrumpf M, Schulze ED, Kaiser K, Schumacher J (2011) How accurately can soil organic C stocks and stock changes be quantified by soil inventories?. Biogeosciences 8: 1193-1212

Schulp CJE, Nabuurs G-J, Verburg PH (2008) Future carbon sequestration in Europe-Effects of land use change. Agriculture, Ecosystems and Environment 127: 251-264

Schwartz D, Namri M (2002) Mapping the total organic carbon in the soils of the Congo, Global and Planetary Change 33: 77-93

Sharma P, Rai SC (2007) Carbon sequestration with land use cover change in a Himalayan watershed. Geoderma 139: 371-378

Shim JP,Warkentin M, Courtney JF, Power DJ, Sharda R, Carlsson C (2002) Past, present and future of decision support technology. Decision Support Systems 33: 111-126

Shrestha BM, Williams S, Easter M, Paustian K, Singh BR (2009) Modeling soil organic carbon stocks and changes in a Nepalese watershed. Agriculture, Ecosystems and Environment 132: 91-97

Smith P (2004) Carbon sequestration in croplands: the potential in Europe and the global context, European Journal of Agronomy 20: 229-236

Smith P (2008) Land use change and soil Carbon dynamics. Nutrient Cycling in Agroecosystems 81: 169-178

Smith P, DS Powlson, et al. (2000) Meeting Europe's climate change commitments: quantitative estimate of the potential for carbon mitigation by agriculture. Global Change Biology 6: 525-539

Smith J, Smith P, Wattenbach M, Zaehle S, Hiederer R, Jones RJA, Montanarella L, Rounsevell MDA, Reginster I, Ewert F (2005) Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. Global Change Biology 11: 2141-2152

Sofo A, Nuzzo V, Palese AM, Xiloyannis C, Celano G, Zukowsky P, Dichio B (2005) Net CO_2 storage in Mediterranean olive and peach orchards. Scientia Horticulturae 107: 17-24

SPSS Inc (2009) PASW Statistics 18.0. Chicago ,IL

StatSoft (2001) STATISTICA (data analysis software system) version 6. www.statsoft.com. Statsoft, Inc.: Tulsa, OK

Steffen W, Grinevald J, Crutzen P, McNeill J (2011) The Anthropocene:conceptual and historical perspectives Phil. Trans. R. Soc. A 369: 842- 867.

Stoate C, Baldi A, Beja P, Boatman ND, Herzon I, van Doorn A, de Snoo GR, Rakosy L, Ramwell C (2009) Ecological impacts of early 21st century agricultural change in Europe—a review. Journal of Environmental Management 91:22–46

Syphard AD, Radeloff VC, Keuler NS, Taylor RS, Hawbaker TJ, Stewart SI, Clayton MK (2008) Predicting spatial patterns of fire on a southern California landscape. International Journal of Wildland Fire 17 (5): 602-613

Tarnocai C, Canadell JG, Schuur EAG, Kuhry P, Mazhitova G, Zimov S (2009) Soil organic carbon pools in the northern circumpolar permafrost region. Global Biogeochemical Cycles: 23 GB2023. 11 pp

Thompson JA, Pena-Yewtukhiw EM, Grove JH (2006) Soil-landscape modeling across a physiographic region: topographic patterns and model transportability. Geoderma, 133 pp. 57-70

Tomlinson RW (2005) Soil carbon stocks and changes in the Republic of Ireland. Journal of Environmental Management 76:7-93

Tornquist CG, Mielniczuk J, Pellegrino Cerri CE (2009) Modeling soil organic carbon dynamics in Oxisols of Ibiruba´ (Brazil) with the Century Model. Soil & Tillage Research 105: 33-43

USDA (1998) Carbon Storage in forests and peatlands of Russia. General Technical Report NE-244. Northeastern Research Station, Forest Service, United States Department of Agriculture. Radnor, PA

VandenBygaart AJ (2006) Monitoring soil organic carbon stock changes in agricultural landscapes: issues and a proposed approach. Canadian Journal of Soil Science 86: 451-463

Van Vuuren D, Kok M, Girod B, Lucas P (2012) Scenarios in Global Environmental Assessments: Key characteristics and lessons for future use. Global Environmental Change (in press) 2012. DOI: j.gloenvcha.2012.06.001

Van Wesemael B, Lettens S, Roelandt C and Van Orshoven J (2004) Changes in soil C stocks from 1960 to 2000 in the main Belgian cropland areas. Biotechnologie, Agronomie , Sociéte et Environnement 8: 133-139

Vejre H, Callesen I, Vesterdal L, Raulund-Rasmussen K (2003) C and nitrogen in Danish forest soils - contents and distribution determined by soil order. Soil Science Society America Journal 67: 335-343

Viaud V, Angers DA, Walter C (2010) Towards landscape-scale modeling of soil organic matter dynamics in agroecosystems. Soil Science Society of America Journal 74: 1-14

Wainwright J, Thornes JB (2004) Environmental Issues in the Mediterranean: Processes and Perspectives from the Past and Present. London: Routledge

Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil O.M. and a proposed modification of the chromic acid titration method. Soil Science 37: 29-38

Wan Y, Lin E, Xiong W, Li Y, Guo L (2011) Modeling the impact of climate change on soil organic carbon stock in upland soils in the 21st century in China. Agriculture, Ecosystems and Environment 141: 23-31

Wang J, Chen J, Ju W, Li M (2010) IA-SDSS: A GIS-based land use decision support system with consideration of carbon sequestration. Environmental Modelling & Software 25: 539-553

Wang S, Wilkes A, Zhang Z, Chang X, Lang R, Wang Y, Niu H (2011) Management and land use change effects on soil C in northern China s grasslands: a synthesis. Agriculture, Ecosystems & Environment 142: 329-340

Watson RT, Noble IR., Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (2000) Land-use. Land-use Change and Forestry. Cambridge: Cambridge University Press

Weber JL (2011) An experimental framework for ecosystem capital accounting in europe. European Environment Agency, Technical Report 13

Wellock WL, LaPerle CM, Kiely G (2011) What is the impact of afforestation on the C stocks of Irish mineral soils? Forest Ecology and Management 262: 1589-1596

Williams JR (1990) The erosion-productivity impact calculator (EPIC) model: a case history. Phylosophical Transactions of the Royal Society of London, series B 329, 421-8

Woodwell GM, Hobbie JE, Houghton RA, Melillo JM, Moore B (1983) Global deforestation: contribution to atmospheric carbon dioxide.. Science 222: 1081-86

Xu X., Liu W, Kiely G (2011) Modeling the change in soil organic carbon of grassland in response to climate change: Effects of measured versus modelled carbon pools for initializing the Rothamsted Carbon model. Agriculture, Ecosystems & Environment 140: 372-381

Zaehle S, Bondeau A, Carter TR, Cramer W, Erhard M, Prentice IC, Reginster I, Rounsevell MDA, Sitch S, Smith B, Smith PC, Sykes M (2007) Projected changes in terrestrial carbon storage in Europe under climate and land-use change, 1990-2100. Ecosystems 10: 380-401

Zdruli P, Kapur S, Çelik I (2011) Soils of the Mediterranean Region. Their Characteristics, Management and Sustainable Use. In: Kapur S, Eswaran H, Blum WEH (Eds.) Sustainable Land Management Learning from the Past for the Future. Springer-Verlag Berlin Heidelberg

Zhang J, Song C, Yang W (2005) Temperature sensitivity of soil respiration and its effecting factors in the different land use [in Chinese]. Acta Scientiae Circumstantiae 25: 1537-1542

Zhao SQ, Liu S, Li Z, Sohl TL (2010) A spatial resolution threshold of land cover in estimating terrestrial carbon sequestration in four counties in Georgia and Alabama. USA. Biogeosciences 7: 71-80

APPENDIX

CARBOSOIL USER GUIDE

Introduction

CarboSOIL has been designed from a mathematical model to predict the amount of C that can be stored in a specific site or profile depending on climate, soil properties, environmental variables and land use (agriculture and forestry). After model validation and calibration a software application has been developed which consists of a Geographic Information System tool integrated in the Arc Toolbox of ArcGIS 10. Users can access the tool through the MicroLEIS DSS system. CarboSOIL tool will be available for download on the website: www.evenor-tech.com/microleis/.

CarboSOIL model is divided into four sub-models according to the different soil sections: CarboSOIL 25 (0-25 cm), CarboSOIL 50 (25-50 cm), CarboSOIL 75 (50-75 cm) and CarboSOIL TOTAL (0-75 cm). Each of these submodels can be executed independently.

Data requirements

Output data

Carbon content in a particular soil profile based on climate, soil, and land use variables (Mg ha^{-1}). Code: SOC

Input data

Climate variables

1. Average temperatures in December, January and February (°C). Code: TDJF
2. Average temperatures in June, July and August (°C). Code: TJJA
3. Annual rainfall (mm). Code: PRPT

Site variables

1. Elevation (m). Code: ELE
2. Slope (%). Code: SLO
3. Drainage. 3 classes :
   - 3.1 Adequate. Code: ad
   - 3.2 Deficient Code: df
   - 3.3 Excessive. Code: ex
4. Soil erosion. 4 classes:
   - 4.1 No erosion. Code:ne
   - 4.2 Sheet erosion. Code: se
   - 4.3 Rill erosion. Code:re
   - 4.4 Gully erosion. Code.ge

Soil variables

1. Nitrogen (g/100 g). Code: NITRO
2. Water pH. Code: PHWA
3. Cation exchange capacity (meq/100 g). Code: CEXC
4. Sand (g/100 g). Code: SAND
5. Clay (g/100 g). Code: CLAY
6. Bulk density (g/cc). Code: BULK
7. Field capacity (meq/100 g). Code: FCAP

Land use variables

1. Land use. 15 classes:
    - 1.1 Other uses. Code: ot
    - 1.2 Non- irrigated areas. Code:nr
    - 1.3 Permanent irrigated areas. Code: pr
    - 1.4 Vineyards. Code: vn
    - 1.5 Fruit trees and berry plantations. Code: fr
    - 1.6 Olive groves. Code: ol
    - 1.7 Complex cultivation patterns. Code: cm
    - 1.8 Agro-forestry areas. Code: af
    - 1.9 Broad-leaved forest. Code: bf
    - 1.10 Coniferous forest. Code: cf
    - 1.11 Mixed forest. Code: mf
    - 1.12 Natural grasslands. Code: gr
    - 1.13 Sclerophyllous vegetation. Code: sc
    - 1.14 Woodland scrubs. Code: wl
    - 1.15 Salt marshes. Code: sm

Getting started

System requirements

CARBOSOIL runs in a GIS environment. To successfully install and run CarboSOIL, the system must meet the following minimum requirements:

Hardware:

Windows PC workstation: Windows XP, Windows Vista, Windows7.

Software:

ArcGIS v.10 with ArcINFO license server and Spatial Analysis extension installed and enabled.

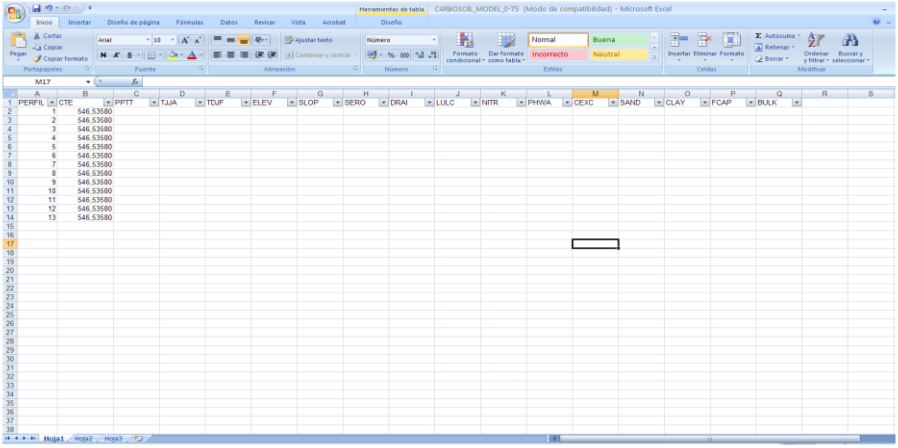
Installation

Follow these steps to download and install CarboSOIL:

1. Download CARBOSOIL.zip and save the folder in C: /.
2. Extract the folder CARBOSOIL.zip in C:/.

Using CarboSOIL

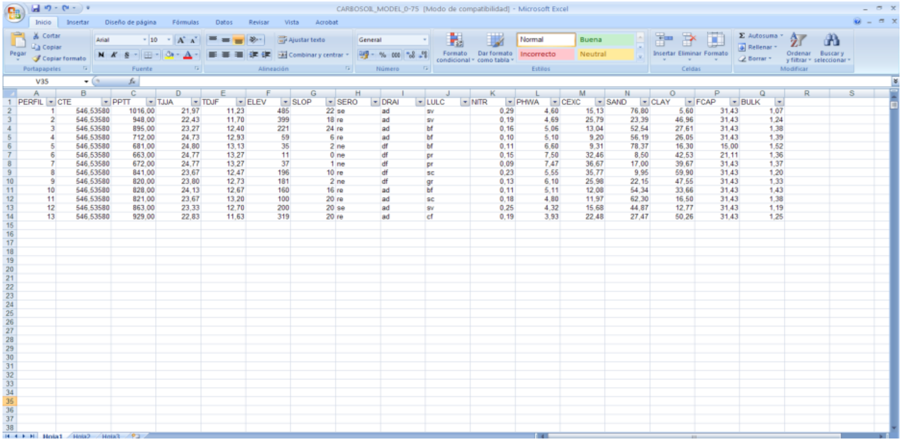
1. Open the folder CARBOSOIL, select CARBOSOIL TOTAL.xls and click *Open*:



CARBOSOIL_MODEL_0-75 [Modo de compatibilidad] - Microsoft Excel

PERFIL	CTE	PPTT	TJJA	TDJF	ELEV	SLOP	SERO	DRAI	LULC	NITR	PHWA	CEXC	SAND	CLAY	FCAP	BULK
1	546,53580															
2	546,53580															
3	546,53580															
4	546,53580															
5	546,53580															
6	546,53580															
7	546,53580															
8	546,53580															
9	546,53580															
10	546,53580															
11	546,53580															
12	546,53580															
13	546,53580															

2. Complete input data in the table. Do not modify fixed cells.



CARBOSOIL_MODEL_0-75 [Modo de compatibilidad] - Microsoft Excel

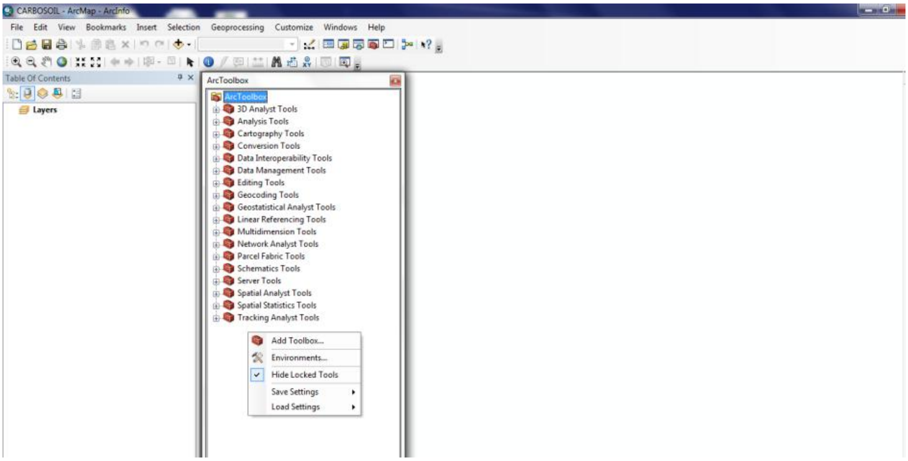
PERFIL	CTE	PPTT	TJJA	TDJF	ELEV	SLOP	SERO	DRAI	LULC	NITR	PHWA	CEXC	SAND	CLAY	FCAP	BULK
1	546,53580	1016,00	21,97	11,23	485	22	se	ad	sv	0,29	4,60	15,13	76,80	5,60	31,43	1,07
2	546,53580	948,00	22,43	11,70	399	18	re	ad	sv	0,19	4,69	25,79	23,39	46,96	31,43	1,24
3	546,53580	895,00	23,27	12,40	221	24	re	ad	bf	0,16	5,06	13,04	52,54	27,61	31,43	1,38
4	546,53580	712,00	24,73	12,93	59	6	re	ad	bf	0,10	5,10	9,20	56,19	26,05	31,43	1,39
5	546,53580	681,00	24,80	13,13	35	2	ne	df	bf	0,11	6,60	9,31	78,37	16,30	15,00	1,52
6	546,53580	663,00	24,77	13,27	11	0	ne	df	pr	0,15	7,50	32,46	8,50	42,53	21,11	1,36
7	546,53580	672,00	24,77	13,27	37	1	ne	df	pr	0,09	7,47	36,67	17,00	39,67	31,43	1,37
8	546,53580	841,00	23,67	12,47	196	10	re	df	sc	0,23	5,55	35,77	9,95	59,90	31,43	1,20
9	546,53580	820,00	23,80	12,73	181	2	ne	df	gr	0,13	6,10	25,98	22,15	47,55	31,43	1,33
10	546,53580	828,00	24,13	12,67	160	16	re	ad	bf	0,11	5,11	12,08	54,34	33,66	31,43	1,43
11	546,53580	821,00	23,67	13,20	100	20	re	ad	sc	0,18	4,80	11,97	62,30	16,50	31,43	1,38
12	546,53580	863,00	23,33	12,70	200	20	se	ad	sv	0,25	4,32	15,68	44,87	12,77	31,43	1,19
13	546,53580	929,00	22,83	11,63	319	20	re	ad	cf	0,19	3,93	22,48	27,47	50,26	31,43	1,25

3. Save table as CARBOSOIL.dbf.

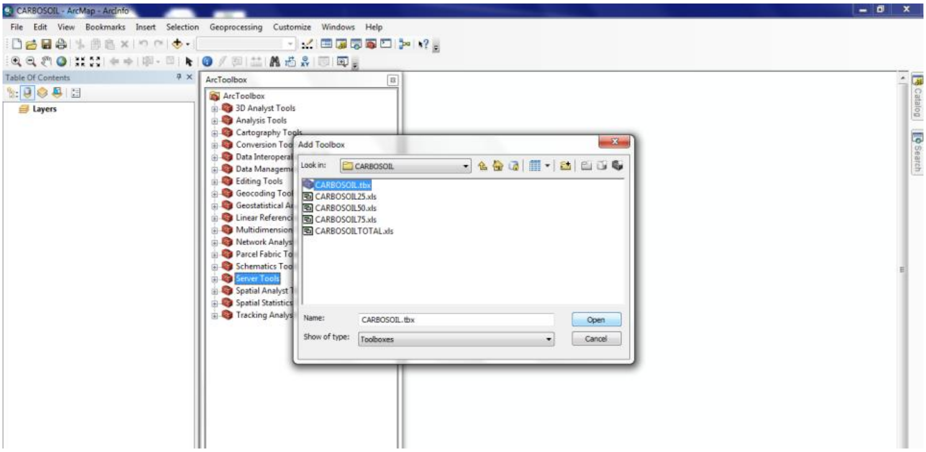
4. Start ArcMap module from the ArcGIS Desktop.

5. Open ArcTool Box from the standard toolbar.

6. Click the empty space of the ArcToolbox window and select *Add toolbox*.



7. In the Windows browser, locate the folder CARBOSOIL and open. Select CARBOSOIL TOTAL.dbf and click *Open*. Do not double click.

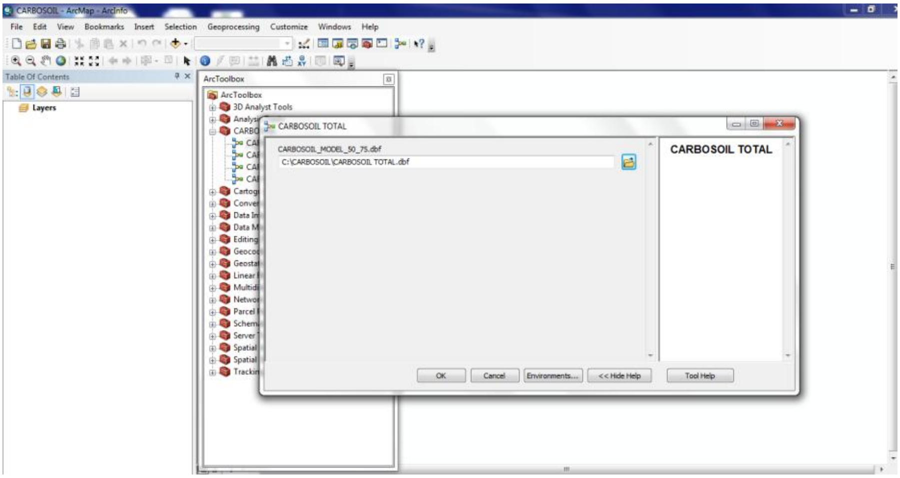


Look in: CARBOSOIL

Name: CARBOSOIL.tbx

Show of type: Toolboxes

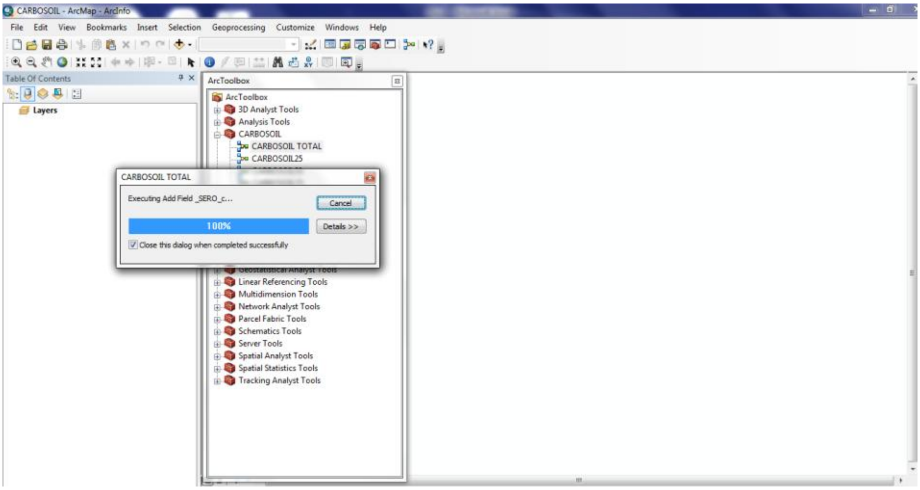
8. On the next screen, click *OK*.



CARBOSOIL_MODEL_50_75.dbf

C:\CARBOSOIL\CARBOSOIL TOTAL.dbf

9. The model will start running, as shown in the following screen.



Executing Add Field _SERO_c...

100%

☑ Close this dialog when completed successfully

10. Browse in Windows C:\CARBOSOIL. Open the table CARBOSOIL.xls. The field SOC (last column of the table) displays the output variable soil carbon content for each profile (Mg ha^{-1}) at 0-75 cm depth.

11. Repeat the previous steps for each of the sub models to obtain soil carbon contents at 0-25, 25-50 and 50-75 cm soil depths.