TESE DE DOUTORAMENTO

Agroforestry Innovation and CAP, impact on climate change, bio-economy and circular economy

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Memoria realizada en la Escola de Doutoramento Internacional (EDIUS) dentro del Programa de Doctorado en Investigación Agraria y Forestal y como parte del proyecto AFINET (H2020 - 727872), bajo la dirección de las profesoras Dra. María Rosa Mosquera Losada y Dra. Nuria Ferreiro Domínguez, para obtener el grado de Doctor por la Universidade de Santiago de Compostela.

Á miña avoa Lola

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Resumen

La Unión Europea (UE), define la agroforestería en el Reglamento 1305/2013 del Pilar II como un sistema de utilización de la tierra en el que se cultivan plantas leñosas perennes (árboles y/o arbustos) en combinación con la agricultura en la misma tierra. Los efectos beneficiosos de la agroforestería han sido ampliamente reconocidos, proporcionando un amplio conjunto de opciones para combatir el cambio climático y las condiciones o eventos climáticos extremos, prevenir la contaminación de las aguas subterráneas, mejorar el reciclaje de nutrientes y preservar la biodiversidad.

El uso excesivo de productos químicos y la ordenación insostenible de la tierra causaron la degradación de los recursos agrícolas necesarios, como el suelo o el agua, con importantes consecuencias ambientales: como la contaminación del agua, la destrucción de árboles, la degradación del suelo, el agotamiento y el uso indebido de los recursos naturales, la pérdida de biodiversidad y la menor resiliencia de las explotaciones agrícolas a los cambios climáticos y del mercado. Para hacer frente a estos desafíos, la futura PAC persigue la vinculación de los sistemas agrícolas con la prestación de servicios ecosistémicos relacionados principalmente con aspectos productivos, ambientales y sociales. Los objetivos de la PAC después de 2020 se centran principalmente en la lucha contra el cambio climático (40% del presupuesto de la próxima PAC), aumentar la sostenibilidad de las explotaciones, proteger los recursos naturales, apoyar los ingresos y la capacidad de recuperación de las explotaciones para mejorar la seguridad alimentaria, aumentar la competitividad de las explotaciones mediante la investigación, la tecnología, la digitalización y proporcionar una mejor posición del agricultor en la cadena de valor tratando de atraer a los jóvenes agricultores. Hoy en día, en el marco de la crisis de la pandemia COVID-19, las instituciones europeas reconocen la importancia de invertir en la protección de la naturaleza, la restauración y la transición de las actuales prácticas agrícolas insostenibles hacia prácticas agrícolas más sostenibles destinadas a alcanzar la neutralidad climática en las explotaciones agrícolas como clave para la recuperación económica de Europa.

La agroforestería es un sistema de utilización de la tierra que puede aplicarse a nivel de parcela, granja y paisaje. Cuando se desarrolla a nivel de paisaje, la circularidad vinculada a los sistemas agrícolas mixtos es clave para fomentar la sostenibilidad en toda Europa. El potencial de la aplicación y, por consiguiente, la obtención de beneficios de los sistemas agrícolas mixtos y la agroforestería es enorme si se tienen en cuenta lo previamente mencionado. Así pues, los cultivos herbáceos, los pastos permanentes y los cultivos permanentes como la agroforestería sólo se utilizan en el 0,1%, el 10% y el 0,1% de estos tipos de utilización de la tierra en Europa, respectivamente.

En Europa, la región biogeográfica del Mediterráneo está particularmente expuesta a los efectos del cambio climático. Las prácticas intensivas convencionales dan lugar a una pérdida de biodiversidad, que está vinculada a la intensificación y al cambio climático, lo que conduce a la degradación del ecosistema y a la reducción del rendimiento de los cultivos como parte de una gama más amplia de daños económicos y sociales. A este respecto, la Comisión Europea estimó un costo de 3,5 a 18,5 billones de euros por año en el período 1997-2011, relacionado con las pérdidas de servicios ecosistémicos, y de 5,5 a 5 billones de euros por año como consecuencia de la degradación de las tierras. La aplicación de la agroforestería en zonas con una elevada presión ambiental, generalmente vinculada a la gestión agrícola intensiva, podría promover un conjunto de beneficios ambientales y fomentar la rentabilidad de las explotaciones agrícolas.

LUCAS (Land Use Cover Aerial Frame Survey) es una encuesta que recoge datos armonizados y comparables de todo el territorio de la UE, basados en estimadores estadísticos para proporcionar una amplia gama de información sobre la cubierta terrestre y el uso de la tierra en Europa. Utilizando el conjunto de datos LUCAS, se reconoció que las tierras de cultivo, los pastizales, los matorrales y los bosques eran las cubiertas terrestres dominantes en la UE-28. Como uso sostenible de la tierra y técnica asociada a la agricultura climáticamente inteligente, la agroforestería cuenta con el apoyo de varias organizaciones internacionales, lo que se perfila como un instrumento prometedor en el marco normativo. Así pues, teniendo en cuenta los desafíos a los que se enfrenta Europa en relación con el cambio climático y la pérdida de biodiversidad, el "Green Deal" Europeo apareció como una hoja de ruta destinada a "transformar la UE en una sociedad justa y próspera, con una economía competitiva y eficiente en el uso de los recursos, sin emisiones netas de gases de efecto invernadero en 2050" y "proteger, conservar y mejorar el capital natural de la UE protegiendo la salud y el bienestar de los ciudadanos de los riesgos relacionados con el medio ambiente". Con ese fin, el Acuerdo Green Deal recoge un conjunto de seis políticas y medidas destinadas a cumplir el Programa de las Naciones Unidas para 2030. La estrategia "de la granja a la mesa", la estrategia de la UE en materia de diversidad biológica para 2030 y el nuevo Plan de Acción sobre la Economía Circular son los pilares fundamentales del Green deal de Europa, en el que la agroforestería aparece como una posible solución.

El fósforo, el nitrógeno y el potasio son nutrientes fundamentales para la producción agrícola y, en el caso del fósforo, un elemento no renovable que compromete seriamente la producción de alimentos en un futuro próximo debido al "pico de fósforo" al disminuir sus reservas mientras aumenta la demanda mundial. Por el contrario, los lodos de depuradora y los biofertilizantes se consideran una enorme y sostenible fuente de nutrientes si se gestionan correctamente. La Estrategia de Bioeconomía de la UE y el Programa "Zero waste" sobre la economía circular son el resultado del renovado impulso de la anterior legislación de la UE que respondía a las crecientes necesidades, el llamamiento de la ciencia a la acción y la conciencia colectiva sobre la degradación del medio ambiente. Como resultado de la aplicación de las Directivas 86/278/CEE y 91/271/CEE de la UE, las zonas urbanas de más de 15.000 habitantes se vieron obligadas a tratar las aguas residuales, lo que produjo como consecuencia una cantidad sustancial de lodos de depuradora que era necesario gestionar y que aumentaría en los próximos años. La Directiva 86/278/CEE de la UE estaba relacionada con el empleo de estos lodos de depuradora en terrenos agrícolas y se transpuso a la legislación local en países del mediterráneo como España (R.D. 1310/1990) que busca el empleo sostenible y seguro de este nuevo insumo evitando los problemas relacionados con la propagación de patógenos y la contaminación por metales pesados.

Dentro de los conceptos de bioeconomía y economía circular, los lodos de depuradora desempeñan una función vital en la UE, permitiendo cerrar el círculo y maximizar el uso de los recursos creados por la necesidad de reducir la contaminación del agua y la mejora del tratamiento de los lodos de depuradora, lo que proporciona un producto de valor añadido a tener en cuenta para sustituir a los costosos fertilizantes inorgánicos y hacer frente a futuros problemas de escasez de nutrientes para la agricultura.

Los sistemas de agroforestales proporcionan un amplio conjunto de respuestas para la sostenibilidad agrícola, abordando mediante un enfoque holístico las propuestas de bioeconomía y economía circular de las instituciones europeas, vinculando las zonas rurales y urbanas de varias maneras bidireccionales. La agroforestería es una práctica intensiva, que necesita un elevado suministro de nutrientes debido a las altas extracciones originadas tanto por las plantas leñosas perennes como por la vegetación herbácea. Sin embargo, la eficiencia en materia de nutrientes de la agroforestería (la proporción de lo que se extrae en comparación con lo que se añade) es mayor que en los monocultivos, lo que aumenta el contenido de biomasa por unidad de superficie que se produce.

El uso de lodos de depuradora "frescos" en la agricultura está prohibido en Europa, siendo necesario tratarlos mediante encalado, compostaje o digestión (ya sea anaeróbica o aeróbica) para reducir los patógenos y mejorar su calidad. Los tratamientos más comunes de los lodos de depuradora son la digestión anaeróbica y el compostaje, siendo los que promueve la UE para ser empleados en agricultura. Además de la importante contribución que se ha destacado anteriormente en cuanto a la adición de nutrientes al suelo, cuando se gestionan correctamente, los lodos de depuradora funcionan como una importante fuente de materia orgánica, impulsando y mejorando la fertilidad del suelo, mejorando la estructura de éste y contribuyendo a la mitigación del cambio climático al promover el almacenamiento de carbono en el subsuelo del suelo y del sistema silvopastoral y en los árboles. Además, el contenido de calcio y materia orgánica en los lodos ayuda a mejorar el pH del suelo y a neutralizar la toxicidad del aluminio en los suelos ácidos, como los de Galicia. Varios estudios sugirieron también un aumento de la producción de pastos vinculado a la fertilización de los lodos de depuradora en los sistemas silvopastorales. Por otra parte, los lodos de depuradora contienen en sí mismos cantidades importantes de metales pesados como el cobre y el zinc, lo que podría crear importantes problemas de toxicidad si se supera el contenido medio en el suelo (basado en el origen de su material original). El mayor contenido de metales pesados en los lodos de depuradora que en el suelo llevó a la Comisión Europea a establecer límites para el contenido de metales pesados en el suelo y a buscar nuevas reglamentaciones que finalmente no fueron aprobadas. En este sentido, el Plan de Acción de la Nueva Economía Circular trabaja en una propuesta para revisar la Directiva 86/278/CEE y actualizarla en el marco del aumento de los conocimientos científicos. Así pues, es fundamental evaluar el estado de los suelos previamente a la adición de lodos para medir las necesidades de fertilización y obtener datos sobre el pH y el contenido de metales pesados en los suelos que deben vincularse al material de la roca madre para estimar las cantidades máximas de metales pesados que pueden añadirse a fin de mantener la salud del suelo. De esta manera se reducirán los problemas de salud humana y animal vinculados a la ingesta de metales pesados a través de la cadena trófica y se contribuirá a una economía circular segura, a la seguridad alimentaria y a la sostenibilidad en su conjunto.

El objetivo de esta tesis es proporcionar un análisis global de la situación actual de las dos prácticas agroforestales más importantes en la región mediterránea de Europa: el silvoarable y la silvopastoreo en zonas de cultivo y pastos, y evaluar la técnica de gestión de explotaciones agrícolas más utilizada a través de una práctica de economía circular que es el reciclaje mediante la fertilización con lodos de depuradora urbana de un sistema de silvopastoreo en Galicia.

Este objetivo general se desdobla en tres objetivos específicos que persiguen analizar el alcance de las prácticas silvoarables, así como el despliegue y la aplicación de las políticas llevadas a cabo en 27 Programas de Desarrollo Rural (Pilar II) en el marco de la PAC 2014-2020, en las zonas mediterráneas de Europa para comprender (i) cómo se promueven las prácticas silvoarables y proporcionar información a los Estados miembros mediterráneos para desarrollar mejores políticas que permitan la adopción de la agroforestería en Europa en el marco de la PAC 2021-2020 en la que los pagos se basarán en los resultados. Esta tesis tiene también como objetivo específico (ii) evaluar la situación actual de los pastizales permanentes en la zona mediterránea de Europa, así como los programas de desarrollo rural que fomentan la silvopastoreo, para comprender mejor cómo se promueven los sistemas de utilización sostenible de la tierra y proporcionar ideas para fomentar la silvopastoreo en toda Europa. Por último, el tercer objetivo específico trata de (iii) evaluar como un enfoque práctico, los cambios en las propiedades químicas (pH) y biológicas (carbono orgánico) del suelo (pH y OM), cuantificando el crecimiento de los árboles (altura dominante y cubierta arbórea) estableciendo relaciones entre la variación de las propiedades químicas y biológicas del suelo y el crecimiento de los árboles durante el período 1998-2012 en un sistema silvopastoral establecido en un suelo forestal ácido bajo P. radiata fertilizado con lodos de depuradora hace 14 años.

Las principales conclusiones destacan que la zona mediterránea de Europa está dominada por la presión antropogénica que se ha modificado en el último siglo tras la revolución verde, lo que ha provocado una intensificación en algunas zonas, pero también el abandono de tierras en los últimos decenios en otras. Esto hace que la mayoría de las prácticas agroforestales (tanto silvopastorales como silvoarables) se sitúen en la zona mediterránea occidental de Europa en las provincias occidentales de España y Portugal. En los últimos decenios, el abandono de tierras, así como las políticas de forestación y reforestación, provocaron una recuperación de los robledales en las zonas mediterráneas, cuyo sotobosque va en aumento y causa muchos problemas sociales relacionados con los incendios forestales que se vieron exacerbados por el cambio climático.

La agroforestería puede aplicarse tanto en el uso de la tierra de los bosques como en el de los cultivos agrícolas (cultivos anuales y permanentes). En lo que respecta a los cultivos permanentes, el olivo es el árbol leñoso perenne más representativo cuando se aplica la agroforestería en tierras de cultivo asociadas a prácticas silvoarables para optimizar el uso de los nutrientes pero también para proteger la erosión del suelo aumentando la sostenibilidad de los olivares. Por otra parte, los robles son el perenne leñoso más importante cuando la agroforestería se implementa como silvopastoreo para extender el período de pastoreo como resultado del beneficio que causan en la producción de pastos y como recurso alimenticio (bellota). Sin embargo, la mayoría de las regiones tienen una baja extensión de silvopastoreo y puede estar vinculada a una presión antropogénica alta (agricultura intensiva) y baja (abandono). Además de los robledales, en algunas regiones del Mediterráneo también predominan las coníferas, pero la extensión de la agroforestería en esas zonas es bastante reducida, porque como especie pionera, los pinos se plantan en zonas marginales de baja productividad para alimentar al ganado y no proporcionan alimento adicional a los sistemas ganaderos como los robles (bellotas).

La extensión potencial de las prácticas agroforestales silvoarables que proporcionan servicios ecosistémicos en la zona mediterránea de Europa es enorme debido a la reducida extensión que tiene actualmente este sistema de uso sostenible de la tierra tanto en tierras de cultivo como en pastizales permanentes. En lo que respecta a las prácticas silvoarables, este tipo de uso de la tierra debería ser promovido por la PAC considerando la promoción de las actividades de los servicios de extensión pero también el desarrollo de cadenas de suministro y valor adecuadas dentro de la estrategia "de la granja a la mesa" y la estrategia de bioeconomía de la UE para cumplir el Green Deal Europeo promovido por la Comisión Europea. Teniendo en cuenta la silvopastoreo, la mayoría de las medidas de silvopastoreo relacionadas con la silvopastoreo se adaptan a las necesidades locales, principalmente asociadas a la regeneración y el mantenimiento en las dehesas gestionadas, pero en otras zonas están vinculadas a la prevención de incendios forestales mediante la promoción de la silvopastoreo en la mayoría de las regiones mediterráneas de Europa.

Los beneficios que proporciona la agroforestería se reconocen en general en la mayor parte de la zona mediterránea de Europa, donde la política fomenta su mantenimiento del establecimiento, sin embargo el presupuesto asignado a estas medidas de política es bastante reducido. La mayoría de las prácticas agroforestales aplicadas en las tierras de cultivo están vinculadas a los elementos del paisaje financiados mediante la aplicación de la medida agroambiental 10.1. El amplio conjunto de servicios ecosistémicos que proporciona la agroforestería es fundamental para la transición europea hacia sistemas de utilización de la tierra más sostenibles, lo que hace necesario promover la agroforestería y la economía circular vinculada a los lodos de depuradora mediante la implantación de laboratorios vivos, el aumento de los conocimientos técnicos entre los agricultores, el suministro de herramientas de gestión para comparar las mejores opciones comerciales, incluido el desarrollo de cadenas de valor para los productos leñosos perennes, así como el desarrollo de sistemas de conocimientos asociados a servicios de extensión adecuados en los que se puedan utilizar experimentos de investigación y granjas innovadoras para difundir la agroforestería. En la PAC posterior a 2020 deberían promoverse instrumentos vinculados a la promoción de los servicios ecosistémicos, grupos operativos y ecoesquemas asociados a la agroforestería.

La gestión de la agroforestería es más compleja que un monocultivo exclusivamente arable o una masa forestal con menor demanda de insumos. La agroforestería es un sistema de uso agrícola intensivo que aumenta la producción de biomasa por unidad de tierra, por lo que debe vincularse a un mayor uso de fertilizantes, que pueden proceder de zonas urbanas como, por ejemplo, los lodos de depuradora. Los lodos de depuradora mejoran el crecimiento de los árboles y, por lo tanto, aumentan la producción de biomasa por unidad de territorio gracias al aumento de la fertilidad del suelo que provoca si se utilizan dosis adecuadas, incluso inferiores al potencial de contaminación por metales pesados. Sin embargo, en la actualidad no se promueve el uso de los lodos de depuradora como fertilizante debido a la falta de comprensión de su potencial. Nuestros resultados muestran que el uso de los lodos de depuradora afectó positivamente al crecimiento de los árboles, ya que éstos se beneficiaron desde el principio cuando su tasa de crecimiento era muy elevada; sin embargo, la extracción de cationes no se compensó con la adición temprana de lodos de depuradora y el aumento de la acidez del suelo en una zona en que las precipitaciones y el material rocoso originario hacen que los suelos se vuelvan ácidos. Esto sugiere que el crecimiento de los árboles puede beneficiarse de la aplicación adicional de lodos de depuradora, sobre todo con dosis bajas. Nuestros resultados muestran que parece aconsejable aplicar enmiendas adicionales con un pH más alto que el del suelo (cal, lodos de depuradora) en los años intermedios de la plantación de árboles para mantener los rangos adecuados de pH y SOC del suelo para compensar las extracciones de cationes por parte de los árboles. El crecimiento de los árboles aumenta la extracción de cationes del suelo y modifica el microclima del sotobosque, lo que disminuye los niveles de pH y SOC del suelo con el tiempo. Sin embargo, se observa un efecto positivo de la fertilización con lodo de depuradora en el pH y la SOC del suelo, principalmente en el caso de las altas dosis de lodo de depuradora en el pH, que no compensaron la extracción de cationes del suelo por parte de los árboles, principalmente en los años posteriores a la aplicación de lodo de depuradora en el suelo. La edad de los árboles y el cierre del dosel es el principal factor que aumenta el carbono del suelo.

Por último, los niveles de SOC variaron en función de la variabilidad de las condiciones meteorológicas, se deben establecer parcelas de control para comprobar si las parcelas gestionadas por los agricultores aumentan la SOC en comparación con las parcelas no gestionadas, independientemente de las condiciones meteorológicas a fin de tener en cuenta el beneficio de las prácticas en la próxima PAC. Los ecoesquemas ofrecen una oportunidad innovadora de cuidar el medio ambiente y el clima, apoyando así la transición hacia sistemas agrícolas más sostenibles y contribuyendo a las emisiones netas nulas en el sector agrícola en 2050, que deberían comenzar en la PAC posterior a 2020.

Palabras clave: Silvoarable; Silvopastureo; Política; Resiliencia; Lodo de depuradora.

Abstract

The European Union (EU), defines agroforestry in Pillar II Regulation 1305/2013 as a land-use system in which woody perennials (trees and shrubs) are grown in combination with agriculture on the same land. The beneficial effects of agroforestry have been widely recognised, providing a large set of options to buffer climate change and extreme climatic conditions or events, prevent groundwater contamination, improve nutrient re-cycling and preserve biodiversity.

The excess of use of chemicals and the unsustainable land management caused degradation of needed agriculture resources such as soil or water with significant environmental consequences: as water pollution, tree destruction, soil degradation, depletion and misuse of natural resources, loss of biodiversity and lower farm resilience to climate and market changes. To face these challenges, future CAP pursues linking farming systems to the delivery of Ecosystem Services mainly related to productive, environmental and social aspects. Post-2020 CAP objectives are mainly focused on fighting climate change (40% of the next CAP budget), increase farm sustainability, protect natural resources, support farm income and resilience to enhance food security, increase farm competitiveness through research, technology, digitalisation and provide a better farmer position in the value chain trying to engage young farmers. Nowadays, within the frame of the COVID-19 pandemic crisis, European Institutions acknowledge the importance of investing in nature protection, restoration and the transition of current unsustainable agricultural practices towards sustainable farming practices aiming at reaching climate neutrality in farms as key for Europe´s economic recovery.

Agroforestry is a land use system that can be implemented at plot, farm and landscape level. When developed at the landscape level, circularity linked to mixed farming systems (MFS) is key to foster sustainability across Europe. The potential of the implementation and, therefore, the delivery of benefits from MFS and agroforestry is enormous based on previous inventories. Thus, arable crops, permanent grasslands and

permanent crops as agroforestry is only used in the 0,1%, 10% and 0,1% of these types of land use in Europe, respectively.

In Europe, the Mediterranean biogeographic region is particularly exposed to climate change effects. Conventional intensive practices result in a biodiversity loss, which is linked to climate change and intensification leading to ecosystem degradation and reduced crop yields as part of a wider range of economical and social damages. In this regard, the European Commission estimated a toll of €3.5-18.5 trillion per year in the 1997-2011 period, related to ecosystem services losses and €5.5-10-5 trillion per year as a consequence of land degradation. AF implementation in areas with elevated environmental pressure, usually linked to intensive agricultural management, could promote a set of environmental benefits and encourage farm profitability.

LUCAS (Land Use Cover Aerial Frame Survey) is a survey that collects harmonised and comparable data of the entire EU territory, based on statistical estimators to provide a wide range of information on European land cover and land use. By using the LUCAS dataset, cropland, grassland, shrubland and woodland were recognised as dominant land covers in EU-28. As sustainable land use and climate-smart agriculture technique, agroforestry is supported by several international organization, emerging as a promising tool in the policy framework. Thus, considering the challenges Europe is facing related to climate change and biodiversity loss, the European Green Deal appeared as a roadmap aiming “to transform EU into a fair and prosperous society, with a resource-efficient and competitive economy with no net emissions of greenhouse gases in 2050” and “protect, conserve and enhance EU´s natural capital protecting health and well-being of citizens from environmental-related risks”. For that purpose, the European Green Deal collects a set of six policies and measures intending to fulfil United Nation´s 2030 Agenda. The Farm to fork strategy, the EU Biodiversity Strategy for 2030 and the new Circular Economy Action Plan are key Europe´s Green Deal mainstays in which agroforestry come along as a potential solution. Phosphorous, nitrogen and potassium are key nutrients for agricultural production and, in the case of phosphorus, a non-renewable element which seriously compromises food production in the close future due to the "peak phosphorous" as its reserves decrease while global demand increases. In contrast, sewage sludge and biofertilizers are considered as an enormous and sustainable source of nutrients if correctly managed. The EU Bioeconomy Strategy and the Zero Waste Programme on circular economy are the renewed impetus result of previous EU legislation responding to increasing needs, scientific call to action and collective consciousness on environmental degradation. As a result of the application of the EU Directives 86/278/CEE and 91/271/CEE, urban areas over 15000 inhabitants were compelled to treat wastewater, producing consequentially a substantial amount of sewage sludge that was needed to be managed and would increase in the upcoming years. The UE Directive 86/278/CEE was related to the employment of this sewage sludge on agricultural land and transposed to local legislation in Mediterranean regions such as Spain (R.D. 1310/1990) seeking for sustainable and safe employment of this new input avoiding problems related to pathogens spread and heavy metals contamination. Within the bioeconomy and circular economy concepts, sewage sludge plays a vital role in the EU, allowing to close the loop and maximize the use of the resources created by the necessity of reducing water pollution and the upgrade on sewage sludge treatment, which provides an added-value product to consider for replacing costly inorganic fertilizers and deal with future nutrients scarcity agricultural issues.

Agroforestry systems provide a large set of responses for agriculture sustainability, addressing through a holistic approach the European Institutions bioeconomy and circular economy propositions by linking rural and urban areas in several bidirectional ways. Agroforestry is an intensive practice, needing for an elevated nutrient supply due to the high extractions originated by both woody perennials and the herbaceous vegetation. However, the nutrient efficiency of agroforestry (the proportion of what is extracted compared with what is added) is higher than in monocrops, increasing biomass production per unit of land.

"Fresh" sewage sludge use in agriculture is forbidden in Europe, being necessary to treat it through liming, compositing or digestion (either anaerobic and aerobic) in order to reduce pathogens and improve its quality. Sewage sludge most common treatments are anaerobic digestion and composting, being the ones promoted by the EU to be used in agriculture. Added to the previously stressed important contribution on nutrients addition to soil, when correctly managed, sewage sludge works as an important source of organic matter, boosting and upgrading soil fertility, improving soil structure and contributing to climate change mitigation by promoting carbon storage in soil and silvopastoral system understory and trees. Furthermore, calcium and organic matter content on sludge helps to enhance soil pH and neutralize aluminium toxicity in acidic soils, like those of Galicia. Several studies suggested also an increase in pasture production linked to sewage sludge fertilization in silvopastoral systems. On the other hand, sewage sludge contains itself significant amounts of heavy metals such as copper and zinc, which could create important toxicity problems if the mean content in the soil (based on their parent material origin) is surpassed. The higher heavy metal content in sewage sludge than in the soil led the European Commission to set limits on heavy metals contents on soil and seek for further regulations that were finally not approved. In this sense, the New Circular Economy Action Plan works in a proposal to review the Directive 86/278/EEC and update it in the frame of scientific knowledge increase. Thus, it is key to assess the state of the soils previously to sludge addition in order to measure fertilization requirements and obtain data on pH and heavy metals content in soils which should be linked to the parent rock material to estimate the maximum amounts of heavy metals that can be added in order to maintain soil health. This will reduce the human and animal health problems linked to heavy metals intake through the trophic chain and contributing to a safe circular economy, food security and sustainability as a whole.

The objective of this PhD is to provide a global analysis on the current status of the two most important agroforestry practices in the Mediterranean region of Europe: silvoarable and silvopasture in arable and pasture areas and to evaluate the most extensively used farm management technique through a circular economy practice which is the recycling through fertilization with urban sewage sludge of a silvopasture system in Galicia.

The general objective consists of three specific aims pursuing to analyze the extent of silvoarable practices as well as the deployment and implementation of policies carried out in 27 Rural Development Programmes (Pillar II) within 2014-2020 CAP framework, in the Mediterranean areas of Europe to understand how (i) silvoarable practices are promoted and provide insights to the Mediterranean Member States to develop better policies for agroforestry adoption in Europe within the Future 2021-2027 CAP framework where payments will be based on results. The second specific objective is to evaluate the current situation of permanent grasslands in the Mediterranean area of Europe as well as the rural development programmes fostering silvopasture to better understand how sustainable land use systems are promoted and provide insights to foster silvopasture across Europe. Finally, the third specific objective deals with (iii) the evaluation as a practical approach, the changes in soil chemical (pH) and biological (organic carbon) properties (pH and OM), quantifying the tree growth (dominant height and tree canopy) and establishing relationships between the variation of soil chemical and biological properties and the tree growth during the period 1998-2012 in a silvopastoral system established on an acidic forest soil under P. radiata fertilized with sewage sludge 14 years ago.

Main conclusions highlight that the Mediterranean area of Europe is being dominated by the anthropogenic pressure which has been modified in the last century after the green revolution causing intensification in some areas but also land abandonment in the last decades in other areas. This makes that most of the agroforestry practices (both silvopasture and silvoarable) are placed in the West Mediterranean area of Europe in the western provinces of Spain and Portugal. In the last decades, land abandonment, as well as the afforestation and reforestation policies, caused a recovery of oaklands in the Mediterranean areas, whose understory is increasing and causes a lot of social challenges related with forest fires that became exacerbated by climate change.

Agroforestry can be implemented in both forest and permanent crops land use. With regard to permanent crops, olive trees are the most representative woody perennial when agroforestry is implemented in arable lands associated to silvoarable practices to optimize the use of nutrients but also to protect soil erosion increasing the sustainability of olive orchards.

On the other hand, oaklands are the most important woody perennial when agroforestry is implemented as silvopasture to extend the grazing period as a result of the benefit they cause in pasture production and as a feed resource (acorn). However, most of the regions have a low extent of silvopasture and can be linked to a high (intensive agriculture) and low (abandonment) anthropogenic pressure. Besides Oaklands, conifers are also dominated in some Mediterranean regions, but the extent on agroforestry in these areas is rather low because as pioneer species, pines are planted in marginal areas with low productivity to feed livestock and they do not provide extra feed to livestock systems such as the oaks (acorns).

The potential extent of silvoarable agroforestry practices delivering ecosystem services in the Mediterranean area of Europe is enormous because of the reduced currently extent that this sustainable land use system has in both arable and permanent grassland lands. With regard to silvoarable practices, this type of land use should be promoted by the CAP considering the promotion of the extension services activities but also the development of adequate supply and value chains within The Farm to Fork and EU Bioeconomy Strategy to fulfil the European Green Deal promoted by the European Commission. Taking into account silvopasture, most of the silvopasture measures related with silvopasture are adapted to the local necessity, mainly associated to regeneration and maintenance in the managed dehesas but linked to forest fire prevention through silvopasture promotion in the majority of the Mediterranean regions of Europe.

The benefits that agroforestry provides are generally acknowledged in most of the Mediterranean area of Europe where policy foster their maintenance of the establishment, however, the budget allocated to these policy measures is rather small. Most of agroforestry practices implemented in arable lands are linked to landscape features funded through the implementation of the agro-environment measure 10.1. The large set of ecosystem services that agroforestry provides is key for the European transition towards more sustainable land use systems, which makes necessary to promote agroforestry and circular economy linked to sewage sludge through the implementation of living labs, increase of technical knowledge among farmers, to provide tools to compare the best business options including the development of value chains for woody perennial products, as well as to develop knowledge systems associated to adequate extension services where research experiments, as well as innovative farms, can be used to spread the agroforestry. Tools linked to foster extension services, operational groups and eco-schemes associated with agroforestry should be promoted in the post 2020 CAP.

Managing agroforestry is more complex than an exclusively arable monocrop or a forest stand which has a lower demand for inputs. Agroforestry is an intensive farm use system that increases biomass production per unit of land therefore it should be linked to higher fertilizer use, that can come from urban areas as, for example, sewage sludge. Sewage sludge improves tree growth and therefore increases biomass production per unit of land thanks to the increase of soil fertility it causes if adequate doses, indeed below the heavy metal contamination potential, are used. However, sewage sludge is not currently promoted to be used as fertilizer due to the lack of understanding of its potential. The use of sewage sludge positively affected tree growth as the tree was benefited from the very beginning when its growth rate was very high, however, the extraction of cations was not compensated by the early sewage sludge addition and increased soil acidity in an area where rainfall and rock parent material make soils to become acidic. This suggests that tree growth may be benefited from additional sewage sludge application mostly with low doses. Our results show that it seems advisable to apply additional amendments with higher pH than the soil (lime, sewage sludge) in the middle-ending years of the tree plantation to maintain adequate ranges of soil pH and SOC to compensate for the cation extractions by trees. Tree growth increases cations extraction from soil and modifies the understory microclimate which decreased the levels of soil pH and SOC in the soil over time. However, a positive effect of the fertilisation with SS on soil pH and SOC is observed, mainly in the case of the high doses of SS on pH, which did not compensate for the cations extraction from the soil by the trees, mainly in the years after the application of SS into the soil. Tree age and canopy closure is the main driver to increase soil carbon in the soil.

Finally, the levels of SOC varied depending on weather conditions variability, control plots should be established to check if the managed plots by the farmers increase the SOC compared with the unmanaged plots, regardless of the weather conditions in order to account the benefit of the practices. Eco-schemes deliver an innovative opportunity to care for the environment and climate, thus supporting the transition towards more sustainable farming systems and contributing to the net-zero emissions in the agriculture sector in 2050, which should start in the post 2020 CAP.

Keywords: Silvoarable; Silvopasture; Policy; Resilience; Sewage sludge.

INTRODUCTION

RESULTS-CHAPTER 1

RESULTS – CHAPTER 2

Introduction

1.1. Defining agroforestry and its benefits

Agroforestry definition has been largely discussed (MacDicken and Vergara 1990; Nair 1993, 1994; Mosquera-losada et al. 2009). The AGFORWARD project, based on the previous definitions, concluded that agroforestry is “the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal systems to benefit from the resulting ecological and economic interactions” (Burgess et al. 2015). Moreover, the European Union (EU), within a legal framework and from a policy perspective, defines agroforestry in Pillar II Regulation 1305/2013 as a land-use system in which trees are grown in combination with agriculture on the same land, being the number of trees per hectare determined by the EU Member States and based on its climatic and environmental conditions, forestry species and agricultural sustainability needs (EU 2013a), while the expanded version of the Measure 8.2 replaces “trees” by woody perennials including trees and shrubs. Hereupon, the final work package policy deliverable of the AGFORWARD project summarised agroforestry definition as “the integration of woody vegetation (first component) in at least two vertical layers on land, with the bottom layer providing an agricultural product such crops or forage/pasture (second component) which may be consumed by animals (third component). The distribution of the woody vegetation can be uneven or evenly distributed and the woody component can deliver an agronomic product (fruit, forage) and some other ecosystem services”, being this agreed by European Agroforestry Federation (EURAF) besides the AGFORWARD partners.

Agroforestry systems beneficial effects have been widely recognised, providing a large set of options to buffer climate change (IPCC 2019a, b, c and d) and extreme climatic conditions or events (IPCC 2014, 2019d), prevent groundwater contamination (USDA 2019), improve nutrient re-cycling and, therefore, re-use of resources and preserve biodiversity (Nair et al. 2010a and b; Rigueiro-Rodríguez et al. 2010;

Mosquera-Losada et al. 2019a). Academic definitions tend to focus on agroforestry benefits derived from its interactions while policy definitions, acknowledge the resulting benefits, defining agroforestry as land cover and land use system.

1.2. Common agricultural policy and agroforestry

The Common Agricultural Policy (CAP) is the EU policy tool for agricultural management, sustainability and rural development through Pillar I and Pillar II regulations 1307/2013 and 1305/2013 respectively (EU 2013a, b). Launched in 1962, the CAP embraces agricultural and societal issues with a common goal, ensures stability in the food supply while improving rural areas standard of living and environmental sustainability. The CAP implementation, with a temporary design frame of seven years, ranged from six countries in its start to 28 nowadays (27 for the new CAP 2021 - 2027 period due to UK´s Brexit). Important reforms were carried out since the beginning of the CAP with an important shift in the way of farming as a consequence of the reduction of ecosystem services delivery from farming systems caused by the agriculture intensification. The excess of use of chemicals and the unsustainable land management caused degradation of needed agriculture resources such as soil or water. This had drastic environmental consequences: water pollution due to an excess of manure and slurries and tree destruction, soil degradation (25% of the EU´s territory is affected by water soil erosion), depletion and misuse of natural resources, loss of biodiversity (60% of protected species and 77% of habitats types are in an unfavourable conservation status) and lower farm resilience to climate and market changes (EEA 2015). Soil degradation became an enormous challenge for the next decades that will need appropriate legal instruments, innovative remediation technologies and practical financial instruments to be solved (EEA 2016). The need for protecting soils ended up in the creation of the EU "Soil mission" (EC 2019a). Water contamination has also become an indeed relevant aspect, conducting to the development of several directives, mainly related to the reduction of the pollutant inputs from rural and urban areas associated with nitrates (EEA 2016). The establishment of voluntary “Codes of good agricultural practices” has become a reality all over Europe as well as the establishment of obligatory measures to be implemented in action programmes for nitrate vulnerable zones (EC 1991). In urban areas, the directive 91/271/EEC, aiming at urban wastewater treatment, increased enormously the amount of sewage sludge produced all over Europe whereas the directive 86/278/EEC, encouraging the use of sewage sludge from urban areas in agriculture, became a reality to protect soils against pollutants such as heavy metals pollution in Europe (EU 1986, 1991).

The increase of the environmental concerns linked to unsustainable practices in urban and rural areas conducted to the development of the different reforms of the CAP. The most important change of farming implementation was fostered through the ‘MacSharry’ reform in 1992, seeking to shift the CAP budget through direct payments from product to land use support. Product support has been decreased since this date and named “coupled payments” as a consequence of the implementation of the Agenda 2000 (EC 1997). This shift set two Pillars in the CAP, Pillar I related to single farm payments to agriculture activity and Pillar II aiming at enhancing Rural Development, considering both environmental and social aspects, which includes forest activity. Furthermore, several directives from 1992 to 2003 drew the slow reduction of coupled payments (Mosquera-Losada et al. 2016c, 2018).

1.3. Agroforestry and sustainable farming transition

The unsustainable use of resources all over the world urged United Nations to develop a common framework to increase sustainability, defining 17 Sustainable Development Goals which became an international handbook for sustainable management and therefore in Europe in 2015. The current and Post 2020 CAP aim to provide not just food for European citizens (EU 2013b, 2016) but also compliance with global strategic policies such as the Sustainable Development Goals (SDGs) (UN 2015a) prioritized in the Seventh European Action Programme (EAP) developed by the European Environment Agency aiming at: (1) “protect, conserve and enhance the Union’s natural capital” (SDG 6, 14 and 15), (2) “develop a resource-efficient, green and competitive low-carbon economy” (SDGs 7, 8, 9, 11, 12 and 13) and (3)“safeguard the Union’s citizens from environment-related pressures and risks to health and well-being” (SDGs 2 and 3) and summarized in 9 objectives (Figure 1) (EC 2014a).

Figure 1. Post-2020 CAP objectives. Source: European Commission.

Therefore, the current and future CAP pursue linking farming systems to the delivery of Ecosystem Services (ES), such as those described in the CICES classes and mainly related with productive, environmental and social aspects: (i) Provisioning services, (ii) Regulation and Maintenance services and (iii) Cultural services. These policy premises are gathered in the nine Some of the post-2020 CAP objectives can be reached through the implementation of mixed farming systems (MFS) and Agroforestry (AF) as shown in Table 1 and highlighted by the EIP-AGRI Focus group on agroforestry and mixed farming systems (EIP-AGRI 2017).

Table 1. Agroforestry fulfilment of the Post-2020 CAP nine objectives. Source: European Commission (EC 2018a).

CAP Post-2020 aims	AF fulfilment
Contribute to climate change mitigation and adaptation as well as sustainable energy	AF is one of the most powerful tools to mitigate and adapt farming systems to climate change (FAO 2013a) while providing biomass-based renewable energy sources.
Foster to sustainable development and efficient management of natural resources such as water, soil and air	AF increases biomass production per hectare thanks to the increase of the sun radiation use and nutrient recycling by tree root uptake the excess of leached nutrients, therefore improving air, soil and water quality.
Contribute to the protection of biodiversity, enhance ecosystem services and preserve habitats and landscapes	AF is able to protect and increase biodiversity thanks to the habitat heterogeneity it creates, but also enhance Ecosystem services delivery (e.g. use of autochthonous breeds and the capacity they have to link habitats and landscapes).
Support viable farm income and resilience across the Union to enhance food security	The optimization of the resources use and the multiple products delivered under AF schemes will increase farm income and food security.

Enhance market orientation and increase competitiveness, including a greater focus on research, technology and digitalisation	Digitalisation, innovation farmer led research and technology development to implement AF foster farm competitiveness through the multiple products delivered from the same land associated with new market opportunities at the local and global level.
Improve the farmers position in the value chain	The increase of the number and quality of products delivered by a farm allows farmers to have a better position in the value chain and be more resilient to climate and market changes.
Attract young farmers and facilitate business development in rural areas	AF systems are complex and need educated and skilled young people that can have on them a business opportunity in the development of the rural areas, including short, medium and long term profits linked to retirement.

Post-2020 CAP objectives are mainly related to fighting climate change (40% of the next CAP budget), increase farm sustainability, protect natural resources, support farm income and resilience to enhance food security, increase farm competitiveness through research, technology, digitalisation and provide a better farmer position in the value chain and attract young farmers.

Nowadays, within the frame of the COVID-19 pandemic crisis, European Institutions stress the importance of investing in nature protection and restoration and on the transition of current unsustainable agricultural practices towards sustainable farming practices aiming at reaching climate neutrality in farms as key for Europe´s economic recovery (EC 2020a). Agroforestry transition, as a way to foster sustainability, can help to improve the results of the three pillars of the sustainable development (income, environment and social), as shown in Figure 2 for MFS and AF.

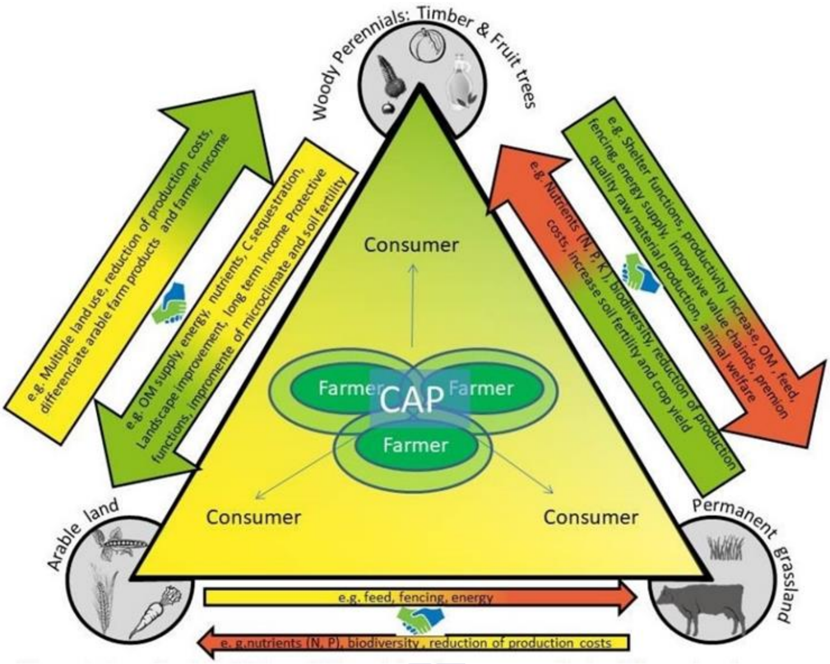

Figure 2. Benefits that MFS (mixed farming systems) and AF (agroforestry) combinations can provide in different land use systems.

The transition of conventional and organic farming systems towards a more sustainable land use such as agroforestry and mixed farming needs to overcome several challenges as those described by over 900 stakeholders involved in the AFINET project (AFINET 2018) linked, on one hand to a better technical and economic knowledge when AF and MFS business models are developed, and on the other hand to favour sustainable food production education (including consumers) while providing better AF and MFS targeted policies. The needed sustainable and climate-friendly farming transition carried out through the implementation of AF and MFS must be implemented by farmers, which make indispensable an approach based on the involvement of multiple actors affecting farming systems in Europe (farmers, researchers, multipliers, retailers, consumers and policymakers), as carried out by the EIP-Agri, and with good practices like the ones gathered by EURAKNOS and EUREKA projects.

Agroforestry is a land use system that can be implemented at plot, farm and landscape level. When developed at the landscape level, circularity linked to MFS is key to foster sustainability across Europe as shown in Figure 3.

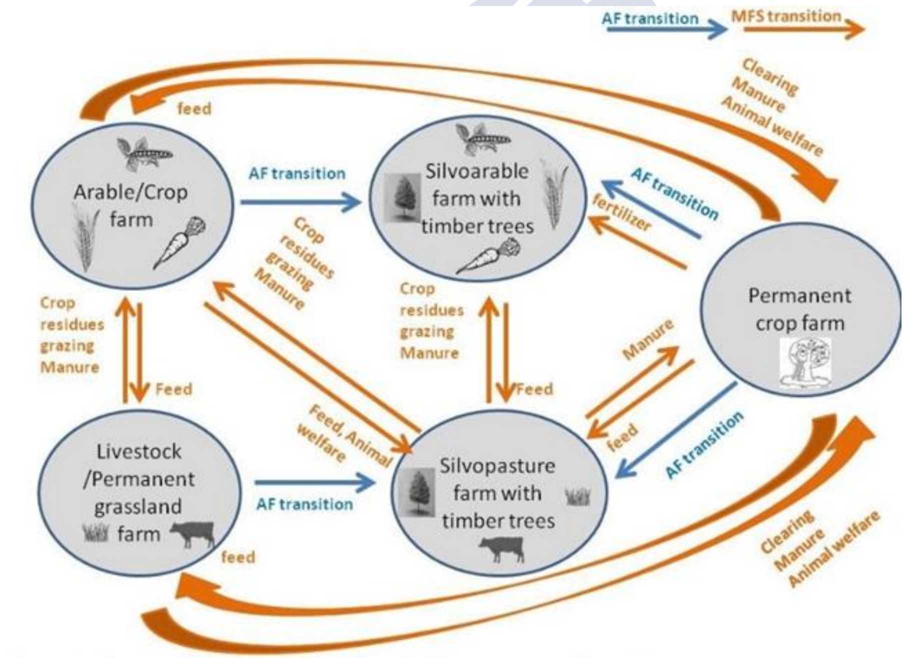

Figure 3. Direct payments land use, AF and MFS main types of transition

1.4. Agroforestry potential in Europe

The potential of the implementation and therefore the delivery of benefits from MFS and AF is enormous based on the inventory carried out by Mosquera-Losada et al. (2018) under the different types of land use paid by the Direct payment aid: Arable crops (AC), Permanent grasslands (PG linked to livestock production) and Permanent Crops as agroforestry is only used in the 0,1%, 10%, 0,1% of these types of land use in Europe, respectively. The potential of the benefits of MFS use in Europe is also high as 47% and 27% of the EU-28 farms are specialized in cropping and livestock systems, respectively, being the remaining MF (24%). Spatial specialization is also important as 25% of the European Livestock numbers linked to specialized FS are placed in 35 of the 975 EU NUTS territorial division but only have the 13% of the agricultural area.

However, the degree of agroforestry implementation across Europe is different (Mosquera-Losada et al. 2016c, 2017) due to their different weather conditions and historical backgrounds. The Mediterranean area is the area with the largest extent of agroforestry in Europe, being also the EU region with the largest set of policy measures implemented (Santiago-Freijanes et al. 2018), usually based in the application of both silvopasture (the most extended AF practice) and silvoarable practices, as the subjacent forms of AF in agricultural lands that can also be implemented in urban areas (homegardens) or forest areas (forest farming) or even combined with linear elements while protecting waters (riparian buffer strips) as stated in Mosquera-Losada et al. (2018a and b). Thus, the first step to foster agroforestry as a sustainable land use system is to understand the historical and anthropogenic actions, the extent they have and the current policies they are implementing.

1.5. Agroforestry and ecosystem services delivery

Climate change affects European stability as a major driver for climate-related risks and hazards. Floods, droughts and forest fires are some of the extreme events that directly impact agriculture and forest management. Furthermore, climate change jeopardizes food security by compromising nutritional quality and animals and plants health (Maggiore et al. 2020). In Europe, the Mediterranean biogeographic region is particularly exposed to climate change effects, being characterised by hot summers and droughts but also a large spectrum of extreme atmospheric processes (Michaelides et al. 2018). According to Kay et al. (2019), 94.4% of farmlands in Europe are under at least one environmental pressure, being arable lands more prone to suffer from environmental pressures than grasslands. Conventional intensive practices result in a biodiversity loss, which is linked to climate change intensification leading to ecosystem degradation and reduced crop yields as part of a wider range of economical and social damages. In this regard, the EC (2020a) estimated a toll of €3.5-18.5 trillion per year in the 1997-2011 period, related to ecosystem services losses and €5.5-10-5 trillion per year as a consequence of land degradation. AF implementation in areas with elevated environmental pressure, usually linked to intensive agricultural management, could promote a set of environmental benefits (Weissteiner et al. 2016; Eurostat 2018). AF systems contribute to nutrients recycling, avoiding groundwater contamination and maximizing resources efficiency (light, water, nutrients), which also encourages farm profitability and carbon sequestering, being recognised as a sustainable land-use tool (Nair et al. 2010a and b). In addition, AF promotes biodiversity (Torralba et al. 2016).

1.6. Agroforestry inventory in Europe

All this policy framework legislate and, therefore, affects land cover and land use, promoting substantial modifications and patterns in farming systems of all over Europe. As a general approach, land cover describes the biophysical cover on earth surface whereas land use illustrates the anthropological utilization of the land, being both concepts different but interrelated since land cover can be used and managed quite differently. Land cover analysis can be performed throughout satellite and aerial imagery in a certain temporary frame, contributing thereby to obtain data on land use. LUCAS (Land Use

Cover Aerial Frame Survey) is a survey that collects harmonised and comparable data of the entire EU territory, based on statistical estimators to provide a wide range of information on European land cover and land use (EUROSTAT 2019). By using the LUCAS dataset, Mosquera-Losada et al. (2016b) identified cropland, grassland, shrubland and woodland as dominant land covers in EU-27, accounting for up to 80% of total land cover, while agriculture and forestry reached up to 76% of land use, including as agriculture agroforestry practices as kitchen gardens, also known as homegardens. As part of the AGFORWARD project, den Herder et al. (2017) reported an extent of 15.4 million ha of agroforestry in Europe, reaching up close to 9% of EU agricultural land although just 358000 ha linked to arable crops and the rest livestock-related agroforestry systems that went up to almost 19.5 million when shrubs, besides trees, are also considered as the woody component of agroforestry practices (Mosquera-Losada et al. 2018a and b). From a policy angle, it is important to consider agroforestry as a dynamic land use system that can be implemented at plot, farm and landscape level involving multiple spatial and/or temporal combinations (e.g. hedgerows as a spatial component of an agroforestry system and silvopasture-intercropping rotation as temporary strategies) that can promote numerous ecological and productive benefits (Mosquera-Losada et al. 2016b).

1.7. Agroforestry and the international strategies

The Orlando Declaration on Agroforestry Systems, as a result of the First World Congress of Agroforestry 2004, sponsored agroforestry as an excellent tool to combat climate change and biodiversity loss related issues. On the same direction, the Global Research Alliance on agricultural greenhouse gases (GRA), an international organization acting as an official observer of the IPCC, which is being integrated by the ministries of 62 countries from all regions of the world, stressed and acknowledged the key role agroforestry plays as Climate Smart Agriculture (CSA) (FAO 2013a and 2013b)to reduce and compensate greenhouse gases emission, including additionally a specific network on agroforestry within its Croplands Research Group. Besides, agroforestry was recognised to fits on CSA concept as a very useful tool to promote climate change mitigation and adaptation through innovation on traditional practices (FAO 2013b). The mentioned CSA concept was launched in 2010 Hague Conference on Agriculture, Food Security and Climate Change, as an innovative approach to develop technical, policy and investment conditions aims to foster sustainability in agriculture and farming for food security under climate change (Mosquera-Losada et al. 2016c). On the light of CSA inception, the Global Alliance for Climate Smart Agriculture (GACSA) was created in 2014 as a multi-stakeholder platform aiming to promote CSA and provide technical advice on CSA practices.

Considering the challenges Europe is facing related to climate change and biodiversity loss, the European Green Deal (EC 2019b) came up as a roadmap aiming "to transform EU into a fair and prosperous society, with a resource-efficient and competitive economy with no net emissions of greenhouse gases in 2050" and "protect, conserve and enhance EU´s natural capital protecting health and well-being of citizens from environmental-related risks". For that purpose, the European Green Deal collects a set of six policies and measures intending to fulfil United Nation´s 2030 Agenda to fulfil EU sustainable development (UN 2015a) and the Paris Agreement about Climate Change (UN 2015b). The Farm to fork strategy, the EU Biodiversity Strategy for 2030 and the new Circular Economy Action Plan are key Europe´s Green Deal mainstays in which agroforestry come along as a potential solution. Besides, a European climate law within the European Climate Pact terms, a European Industrial Strategy and the EU strategies for energy system integration and hydrogen complete the battery of tools within the Green Deal frame to achieve its goals. The farm to Fork strategy highlights agroforestry as a sustainable practice to promote with EU funding, aiming to ensure more sustainable food systems by reducing 50% the use of chemical pesticides and nutrient losses and at least 20% fertilizer use by 2030 (EC 2020b). Agroforestry systems can facilitate the reduction of biocides and fertilizer use by diminishing nutrient, water and soil losses based on high species diversity (Burgess and Rosati 2018). Thereupon, practices as windbreaks and shelterbelts favour a reduction in both biocides and fertilizer application by reducing the damaging actions of wind (erosion, evapotranspiration), promoting nutrients recycling due to the tree roots nutrient uptake, and providing shelter and welfare to animal breeds (Dix et al. 1995; Somer 2019; Zhu et al. 2019). In this regard, the EU Biodiversity Strategy stresses the EU compromise to restore degraded ecosystems by increasing biodiversity-rich landscape features on agricultural land, working to support both nature and farming sustainability in the coming years through its conjunction with the aforementioned Farm to Fork Strategy and the new CAP (EC 2020a). European and global food security is capital to ensure a better future linked to agroecological intensification techniques that increase sustainable productivity (Tscharntke et al. 2012). Farmland birds and pollinator insects are considered agroecosystems health indicators, whose population downtrend can be reversed and beneficiate from agroforestry systems expansion, instead of intensive agriculture, enhancing agricultural production and food security. To achieve it, the EU Biodiversity Strategy sponsor agroforestry systems by proposing to reshape at least 10% of the agricultural area under high-diversity land-use practices. Silvopastoral practices are recognised as a useful tool to modify forests understory biodiversity (Barbier et al. 2008; Mosquera-Losada et al. 2009a and b) since adequate canopy density (Fernández-Núñez et al. 2014) and livestock species, through selective browsing and trampling, favour its conservation. The EU policymakers launched in 2012 the EU Bioeconomy Strategy, updated on 2018, and in 2014 a Zero Waste Programme on circular economy. European guidelines propose both bioeconomy and circular economy as potential solutions to fight climate change, reduce environmental pressures, degradation, and boost sustainability by maximizing products lifecycle while reducing waste concerns (EC 2012, 2014b). The 2018 Global Bioeconomy Summit defined bio-economy as "the production, utilization and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes and service across all economic sectors aiming towards a sustainable economy" (GBS 2018). Circular economy maintains the added value of the products beyond its life, through reutilisation, creating more value instead of wastes. Value chains transformation plays a key role in the circular economy, modifying business and market models (EC 2014b). Agroforestry systems promote and fulfil bioeconomy and circular economy objectives providing a huge range of combinations and tools to achieve multiple objectives on sustainable management of lands and ecosystems. Thus, agroforestry fits on bioeconomy as an important source of biofuels that can replace fossil fuels, reducing carbon footprint and generating alternative employment opportunities in rural areas. Silvopastoral systems benefit from biofertilizers, promoting tree growth and understory production while reinforcing circular economy and promoting carbon storage. The EU proposal of a Circular Economy Action Plan, as part of the European Green Deal, pushes for a complete redesign of supply chain reducing and turning wastes into recycled inputs.

1.8. Agroforestry and fertilization with sewage sludge, a circular economy approach

World population is expected to increase to nine billion people in the upcoming decades, which jeopardizes food and resources sustainability and, therefore, world stability and humanity. Phosphorous, nitrogen and potassium are key nutrients for agricultural production and, in the case of phosphorus, a non-renewable element which seriously compromises food production in the close future due to the "peak phosphorous" as its reserves decrease while global demand increases (Cordell 2010). In contrast, sewage sludge and biofertilizers are considered as an enormous and sustainable source of nutrients if correctly managed. Taking the aforementioned into consideration, the EU Bioeconomy Strategy aims to promote a new regulation on biofertilizers by gathering and standardizing the different national legislations to promote its fabrication and distribution at EU scale. Thereupon, the European Commission started to reviewing in 2016 UE regulation on fertilizers to promote a bio-nutrients market ensuring biofertilizers quality and safety standards (EC 2016a) but, unfortunately, excluding urban sewage sludge due to its pollutant components, stressing heavy metals as the main concern related to toxicity.

The EU Bioeconomy Strategy and the Zero Waste Programme (EC 2014b, 2018b) on circular economy are the renewed impetus result of previous EU legislation responding to increasing needs, scientific call to action and collective consciousness on environmental degradation. Thus, EU Directives 86/278/CEE and 91/271/CEE (EU 1986, 1991) emerged as a necessity to face water pollution problems in the EU as wastewater were directly discharged on rivers and sea. As a result of the application of the aforementioned Directives, urban areas over 15000 inhabitants were compelled to treat wastewater, producing consequentially a substantial amount of sewage sludge (FAO 2013b) that was needed to be managed and would increase in the upcoming years. The UE Directive 86/278/CEE was related to the employment of this sewage sludge on agricultural land and transposed to local legislation in Mediterranean regions such as Spain (R.D. 1310/1990 (BOE 1990)) seeking for sustainable and safe employment of this new input avoiding problems related to pathogens spread and heavy metals contamination. This is a precursor and perfect example of how bioeconomy and circular economy will play a vital role, allowing to close the loop and maximize the use of the resources since the necessity of reducing water pollution and the upgrade on sewage sludge treatment provide an added-value product to consider for replacing costly inorganic fertilizers and deal with future nutrients scarcity issues.

Agroforestry is an intensive practice needing more nutrient supply due to the high extractions originated by both woody perennials and the herbaceous vegetation. However, the nutrient efficiency of agroforestry (the proportion of what is extracted compared with what is added) is higher than in monocrops, increasing organic matter contents. Agroforestry systems provide a large set of responses, addressing through a holistic approach the European Institutions bioeconomy and circular economy propositions by linking rural and urban areas in several bidirectional ways. Silvopasture practices provide economical and ecological advantages such as farm product diversification, prevention of both forest fires and soil erosion and promotion of biodiversity. “Fresh” sewage sludge use in agriculture is forbidden in Europe, being necessary to treat it through liming, compositing or digestion (either anaerobic and aerobic) in order to reduce pathogens and improve its quality (BOE 1990; EC 2001). Sewage sludge most common treatments are anaerobic digestion and composting being the ones promoted by the EU (Amador-García 2017). Added to the previously stressed important contribution on nutrients addition to soil, when correctly managed, sewage sludge works as an important source of organic matter, boosting and upgrading soil fertility, improving soil structure and contributing to climate change mitigation by promoting carbon storage in soil and silvopastoral system understory and trees. Furthermore, calcium and organic matter content on sludge helps to enhance soil pH and neutralize aluminium toxicity in acidic soils, like those of Galicia. Several studies suggested also an increase in pasture production linked to sewage sludge fertilization (Mosquera-Losada et al. 2006, 2016a) in silvopastoral systems (López-Díaz et al. 2007; Rigueiro-Rodríguez et al. 2008; Ferreiro-Domínguez et al. 2014). On the other hand, sewage sludge contains itself significant amounts of heavy metals such as copper and zinc, which could create important toxicity problems if the mean content in the soil (based on their parent material origin) is surpassed. The higher heavy metal content in sewage sludge than in the soil led the European Commission to set limits on heavy metals contents on soil (EU 1986) and seek for further regulations (EC 2000, 2008) that were not approved. The New Circular Economy Action Plan to progress with a proposal to review the Directive 86/278/EEC and update it in the frame of scientific knowledge increase (EC 2020c). Thus, Tchounwou et al. (2012) and Amador-García (2017) found it is key to assess the state of the soils previously to sludge addition in order to measure fertilization requirements and obtain data on pH and heavy metals content in soils which should be linked to the parent rock material to estimate the maximum amounts of heavy metals that can be added in order to maintain soil health. This will reduce the human and animal health problems linked to heavy metals intake through the trophic chain and contributing to a safe circular economy, food security and sustainability as a whole.

Objectives

This PhD aims to provide a global analysis on the current status of the two most important agroforestry practices in the Mediterranean region of Europe: silvoarable and silvopasture in arable and pasture areas and to evaluate the most extensively used farm management technique through a circular economy practice which is the recycling through fertilization with urban sewage sludge of a silvopasture system in Galicia.

This general objective will be developed in three specific and forthcoming chapters aiming at:

1.- Analyzing the extent of silvoarable practices as well as the deployment and implementation of policies carried out in 27 Rural Development Programmes (Pillar II) within 2014-2020 CAP framework, in the Mediterranean areas of Europe to understand how silvoarable practices are promoted and provide insights to the Mediterranean Member States to develop better policies for agroforestry adoption in Europe within the Future 2021-2027 framework where payments will be based on results.

2.- evaluating the current situation of permanent grasslands in the Mediterranean area of Europe as well as the rural development programmes fostering silvopasture to better understand how sustainable land use systems are promoted and provide insights to foster silvopasture across Europe.

3.- evaluating the changes in soil chemical (pH) and biological (organic carbon) properties (pH and OM), quantifying the tree growth (dominant height and tree canopy) and establishing relationships between the variation of soil chemical and biological properties and the tree growth during the period 1998-2012 in a silvopastoral system established on an acidic forest soil under P. radiata fertilized with sewage sludge 14 years ago.

Results

Chapter 1. AGROFORESTRY POLICY PROMOTION IN ARABLE MEDITERRANEAN AREAS

1.1. Abstract

Silvoarable is a type of agroforestry practice where a woody component is deliberately integrated with an arable crop as part of the understory. The silvoarable extension in Europe is rather small in spite of the enormous ecosystem benefits that silvoarable can provide to arable lands, which makes very important to develop policies to foster silvoarable practices in Europe. This paper aims at analyzing the extent of silvoarable practices in Europe as well as analyse the policies measures uses in Europe to understand how silvoarable practices are promoted and provide insights to Mediterranean Member States to develop better policies for agroforestry adoption in Europe within the Future 2021-2027 framework where payments will be based on results. The reduced extent of silvoarable agroforestry practices delivering ecosystem services in the Mediterranean area of Europe is enormous because of the reduced currently extent that this sustainable land use system has. Silvoarable practices should be promoted by the CAP considering the promotion of the extension services activities but also the development of adequate supply and value chains within The Farm to Fork and EU Bioeconomy Strategy to fulfill the European Green Deal promoted by the European Commission.

1.2. Introduction

Climate change affects all regions of Europe and therefore the way about how farming systems should be implemented (IPCC 2019). The Mediterranean biogeographic region of Europe occupies close to 11% of the land of Europe with specific climate conditions that constrain both the way of farming and the potential productivity (EEA 2002). The last decades of intensification of arable farming systems have conducted to a reduction of the natural capital resources mainly associated with European soils that was more intense in the Mediterranean region (RISE 2014). This region is mainly characterized by a clear scarcity of water, uneven annual precipitation distribution and long summer droughts (EU 2007) that reduces potential crop production in spite of its high level of incoming radiation. Moreover, climate change has and will have the greatest negative impact on this area (IPCC 2013), being one of the most climate vulnerable areas in the world.

Silvoarable is defined as an agroforestry practice aiming at integrating woody perennials (trees and/or shrubs) and an agricultural crop growing as part of the understory (Mosquera-Losada et al. 2018b) and is usually associated with the delivery of more ecosystem services than monocultures in agricultural lands (Kay et al. 2018, Mosquera-Losada et al. 2018a, Santiago-Freijanes et al. 2018a; Paris et al. 2019). The United Nations (UN) has identified agroforestry -and therefore silvoarable practices- as one of the most powerful tools to mitigate and adapt farming systems to climate change (IPCC 2019). However and despite silvopasture practices were extensively used in the Mediterranean area in the past (Papanastasis et al. 2008), its extent is currently very low Europe (Den Herder et al. 2017, Mosquera-Losada et al. 2018b). Main challenges for the lack of implementation of agroforestry in Europe have been highlighted by over 900 actors in the AFINET European project (AFINET 2020), who provided the following four main challenges (i) how to establish and manage agroforestry practices, (ii) the economic benefits that agroforestry provides when compared with conventional farming systems currently implemented, (iii) adequate development of the value chains of the multiple products that agroforestry and consumers awareness and finally (iv) the lack of adequate policies aimed at supporting agroforestry systems (Santiago-Freijanes et al. 2018c, Mosquera-Losada et al. 2018b).

The Common Agricultural Policy (CAP) is a key force to foster transition towards agroforestry among farmers in Europe and it has to take into account the three pillars of sustainability: social, environmental, and economic. Up to now, adaptation of the CAP activities implemented at local level is more linked to the Pillar II or the Rural Development Programs (RDP) of the CAP, which are cofounded by the EU member states, but this may change with the new strategic plans because each country has to provide concrete actions to fulfil the targeted nine economic, environment and social aims of the forthcoming CAP 2021-2027 (EU 2020).

This paper aims at analyzing the extent of silvoarable practices as well as the deployment and implementation of policies carried out in 27 Rural Development Programmes (Pillar II) within 2014-2020 CAP framework, in the Mediterranean areas of Europe to understand how silvoarable practices are promoted and provide insights to Mediterranean Member States to develop better policies for agroforestry adoption in Europe within the Future 2021-2027 framework where payments will be based on results.

1.3. Materials and methods

LUCAS analysis

Silvoarable practices are defined as those practices where widely spaced woody vegetation is inter-cropped with annual or perennial crops (Mosquera-Losada et al. 2018). In silvoarable practices, woody perennials (trees/shrubs) can be evenly or unevenly distributed with isolated/scattered trees, hedges and line belts design. Riparian buffer strips can be considered as silvoarable practices when they are in between arable lands and water bodies, being important to protect continental waters, where high inputs of fertilizers are usually applied causing heavily contaminated water (Klapproth and Johnson 2009). Landscape features are also included as part of the evaluation of silvoarable practices since they are usually associated to arable lands (Vidrih et al 2008) to provide pollination ecosystem services but also as a reservoir to deliver beneficial insects to counteract arable crops plagues and finally to increase production, which was reduced due to strong winds.

In this study, "The Land use/cover area frame statistical survey", abbreviated as LUCAS was used to identify silvoarable agroforestry practices (Mosquera-Losada et al. 2018b) including relative to linear elements linked to landscape features such as isolates trees, trees in line… (EUROSTAT 2016; Santiago-Freijanes 2018c). The LUCAS survey micro-data collection of cover and land uses is a freely available EUROSTAT database (EUROSTAT 2013). In this study, we employed the LUCAS survey obtained in 2012, the year before Croatia became the 28th EU member state, so the results are only referred to the EU27. LUCAS is a two-phase sample survey. The first phase is a systematic sample with points spaced 2 km (around 1.1 million different points). In a second phase, a representative subset of 270,267 points was selected for visit in situ by the field inspectors in 2012.

LUCAS uses a double classification system for land covers that also includes the land use with multiple layers, used only for specific landscapes. For example, in agroforestry practices, a woody vegetation layer (LC1) is typically accompanied by a secondary layer (LC2) composed of crops or grass. To identify silvoarable agroforestry systems the combinations of LC1 and LC2 must indicate intercropped permanent crops, woodlands or shrubland. However, there are some limitations to this method, e.g. LUCAS dominant "woodland type" of land cover does not consider the category "land use", and for this reason, most of the broadleaved woodland linked to a relevant agricultural activity (Dehesa, Montado) is not directly recognized.

The agroforestry practices identification was based on the combination of two land covers which integrates a woody component (LC1) and an agricultural activity linked to an arable crop as carried out by Mosquera-Losada et al (2018b) and shown in Table 1. The presence of homegardens, understood as an annual crop combined with woody perennials (usually fruit trees) in urban or semi-urban areas (Mosquera-Losada et al. 2018), was marked by the land use fields (LU1 and LU2).

Land cover / variable	Code	LUCAS class	Arable AGF
Cereals	B11	Common wheat	LC2
	B12	Durum wheat	LC2
	B13	Barley	LC2
	B14	Rye	LC2
	B15	Oats	LC2
	B16	Maize	LC2
	B17	Rice	-
	B18	Triticale	LC2
	B19	Other cereals	LC2
Root crops	B21	Potatoes	LC2
	B22	Sugar beet	-
	B23	Other root crops	LC2
Non-permanent industrial crops	B31	Sunflower	LC2
	B32	Rape and turnip rape	-
	B33	Soya	-
	B34	Cotton	-
	B35	Other fibre and oleaginous crops	LC2
	B36	Tobacco	LC2
	B37	Other non- permanent industrial crops	-
Dry pulses, vegetables and flowers	B41	Dry pulses	LC2
	B42	Tomatoes	LC2
	B43	Other fresh vegetables	LC2
	B44	Floriculture and ornamental plants	LC2
	B45	Strawberries	LC2
Fodder crops	B51	Clovers	LC2
	B52	Lucern	LC2
	B53	Other leguminous and mixtures for fodder	LC2
	B54	Mix of cereals	LC2

Land cover / variable	Code	LUCAS class	Arable AGF
Permanent crops: fruit trees	B71	Apple	LC1
	B72	Pear	LC1
	B73	Cherry	LC1
	B74	Nut trees	LC1
	B75	Other fruit trees and berries	LC1
	B76	Oranges	LC1
	B77	Other citrus fruit	LC1
Other Permanent crops	B81	Olive groves	LC1
	B82	Vineyards	LC1/LC2
Permanent industrial crops	B84k	Mulberries and carob	LC1
	B84m	Willow	-
Woodland	C10	Broadleaved woodland	LC1
	C21	Spruce dominated woodland	-
	C22	Pine dominated woodland	LC1
	C23	Other coniferous woodland	LC1
	C31	Spruce dominated mixed woodland	-
	C32	Pine dominated mixed woodland	LC1
	C33	Other mixed woodland	-
Shrubland	D10	Shrubland with sparse tree cover	LC1
	D20	Shrubland without tree cover	LC1

LC1 = Primary land cover
LC2 = Secondary land cover

Table 1. Criteria used for identifying the silvoarable practices

To estimate the extent of agroforestry of silvoarable and homegardens in hectares at RDP region level, we divided the number of points coded as agroforestry in each territory by the total number of LUCAS points in this territory and multiplied this by the surface of the territory (Mosquera-Losada et al 2018b).

A different approach was used to categorize riparian buffer strips based on the Santiago Freijanes (2018c) methodology using the 270,267 LUCAS points where surveyors identified features that touched the 250 m transects coming from each of the 270,267 points. In addition, the length occupied by the different features of these points were measured in 1283 transects, allowing at some extent to quantify how many meters are occupied by a particular feature identified as LFLM (landscape features mean length). Estimating the hectares occupied by each landscape feature was based on the counting of the number of times that they appear in each specific transect that was multiplied by LFML. The result was added for all transects of 250 m at regional level and divided by the total number of transects, therefore obtaining the percentage of a specific landscape feature length in each transect. To determine riparian buffer strips, those hedgerows close to running waters or water bodies were extracted from the hedgerows database and processed. The percentage of a feature per transect was multiplied by the total surface of each region to provide an indicator of the number of hectares that each landscape feature occupies that may be also used in the future in order to estimate the evolution of the landscape features among LUCAS surveys.

Policy analysis

The policy analysis was conducted considering the measures activated by the Pillar II of the CAP (EU 2013a and b) designed by 27 Member States (all excepting Greece and Cyprus) as their Rural Development Programmes for the period 2014-2020, which are available on the internet (EC 2016) as carried out by Mosquera-Losada et al (2018b).

Upscaling

The obtained geographical indicators from LUCAS (percentage and number of hectares), as well as the policy indicators (activated measures), were upscaled and mapped per region of Europe by using QGIS 2.18. Both forest ownership and altitude have been processed with QGIS 2.18.

1.4. Results

Mediterranean agriculture

Figure 1 shows the dominant type of land cover in the regions of the Mediterranean area of Europe. Only two regions of the Mediterranean European area placed in Spain (Castilla la Mancha and Castilla y León) are dominated by annual crops, while La Rioja (vineyards), as well as Andalucia (olive) in Spain and Puglia (olive) in Italy, are mainly occupied by permanent crops. Grassland without tree/shrub cover is the dominant land cover in Sicilia. The rest of the regions are mainly dominated by woody vegetation linked to pastures such as grassland with sparse tree/shrub cover (Madrid), shrublands without tree cover (Aragón and Malta) and the rest by broadleaved woodlands.

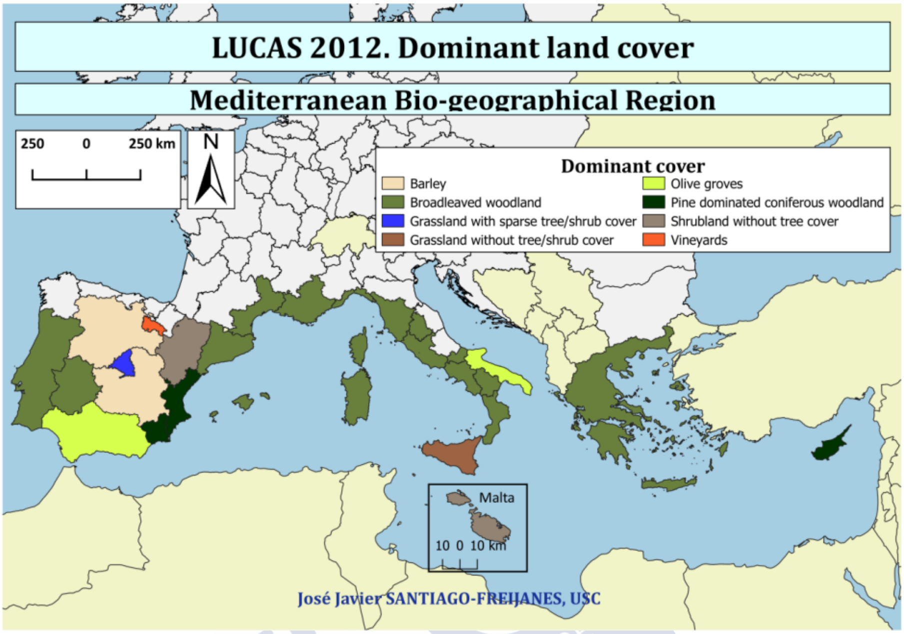

Figure 1. Share of dominant land cover in the Mediterranean Regions of Europe.

The Mediterranean cropland region of Europe (Figure 2) is mostly associated to cereal production such barley, followed by wheat (common and durum) and also a mix of cereals as the understory silvoarable component in most of Spain, and central Italy. Areas like Portugal and the dehesa, South of France, the Italian and French Islands as well as the Northwest of Italy (excluding Liguria) are dominated by grasslands without trees/shrub cover in agricultural lands. These grasslands are usually associated to pastures which are ploughed at least every 5 years (if over, they are considered permanent grasslands) while annually harvested. Barley is the most extensive cropland in the Central and Northeast regions of Spain.

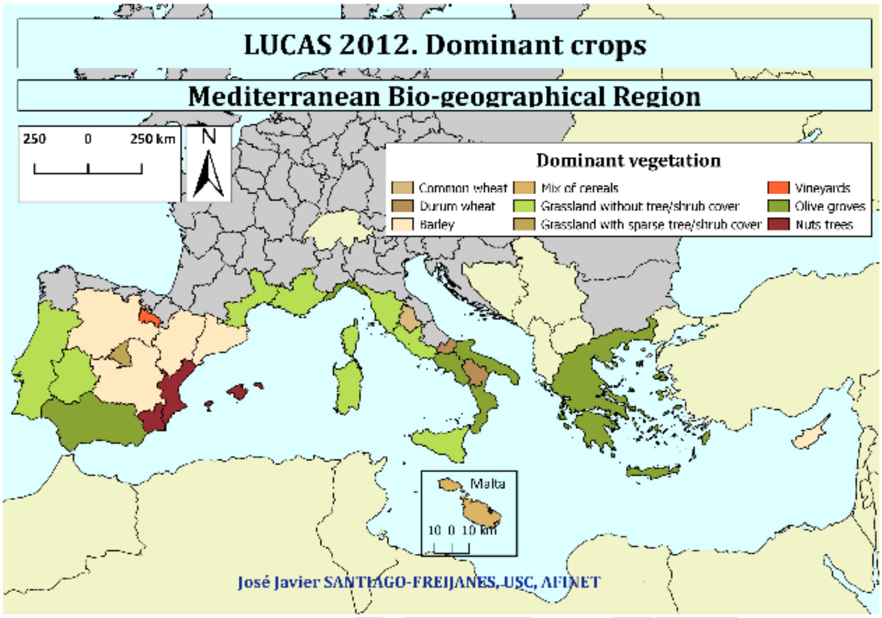

Figure 2. Share of dominant crop species and fallow land in the Mediterranean Regions of Europe.

When the woody component of the silvoarable practice as part of the agricultural land is evaluated and shown as permanent crops, it can be seen that there are regions dominated by orchards of olive trees but also nut trees. Olive groves dominate most of Greece, Andalucía, and Italy (Calabria, Liguria, Campania and Puglia). The Spanish regions of Valencia, Islas Baleares and Murcia are dominated by nut trees (i.e. almonds…).

Mediterranean agroforestry

Silvoarable practices in Europe linked to arable lands ranged from 0 to 2.57 % in spite of the benefits that silvoarable has for this type of areas (Figure 3). Silvoarable practices are especially relevant in the dehesa areas such as Portugal, Extremadura and Madrid in the Iberian peninsula but also in Baleares (Spain), Campania, Basilicata and

Toscana in Italy, being underrepresented in Greece, France and the eastern regions of Spain with low populated areas. Riparian buffer strips are most evenly distributed in the Mediterranean countries being generally more relevant in those highly populated regions linked to coastal areas (Figure 3). Attending to the EUROSTAT (2012) data, most of silvoarable practices are cropped with the legume lucern (17.86%), followed by flowers (14,29%) and vegetables (10.71%) and maize, potatoes and sunflowers, reaching a share around 7% each of them. The aforementioned dominant cover crops, such as barley and wheat are only combined in silvoarable practices in a much lower share of around 3.5%. Silvoarable practices are mainly carried out under olive trees (42,86%) followed by oak lands (21,43%), but also related to apple trees (10,1%) and other fruit trees (10.7%) and nut and nurseries with a share of 7.14%.

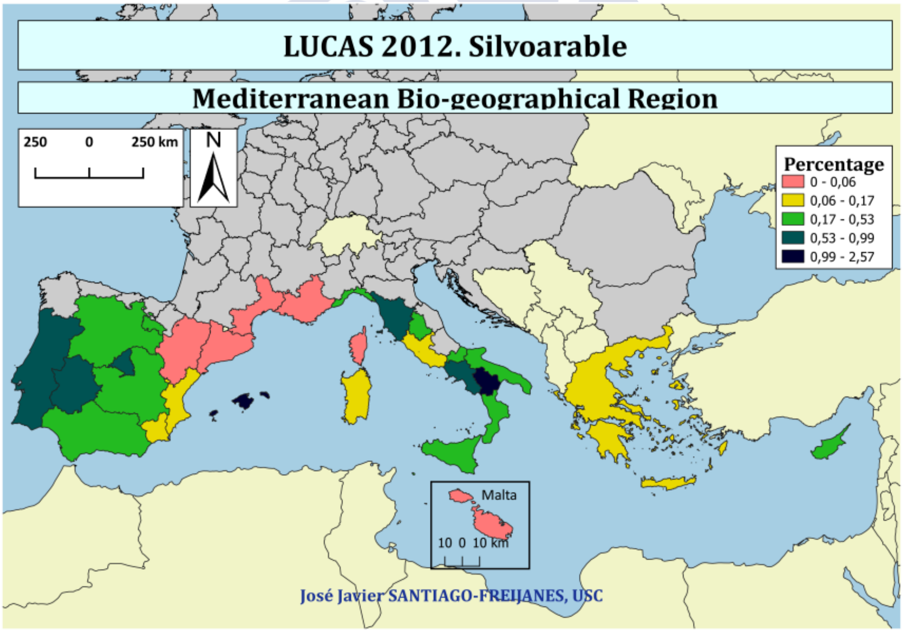

Figure 3. Percentage of land occupied by silvoarable agroforestry practices silvoarable in agricultural lands.

Silvoarable agroforestry practices linked to permanent crops (also known as orchards) are more associated with annual crops than with ungrazed temporary grasslands (Figure 4). Portugal presents a high share of both types of crops in orchards while Greece has silvoarable practices mostly associated to temporary grassland. Generally, those areas with a higher share of annual crops have a lower share of temporary grassland in Italy.

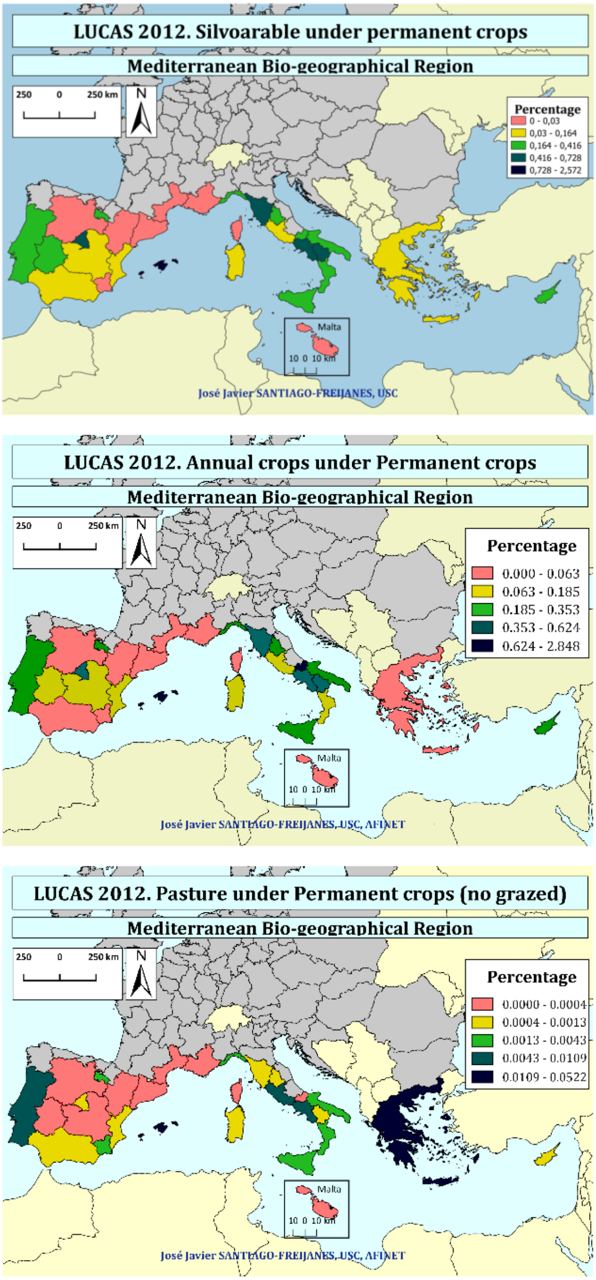

Figure 4. Percentage of silvoarable (top) linked to permanent crops and share of annual crops and no-grazed temporary grassland (bottom).

Silvoarable practices linked to woodlands are predominant when compared with those linked to shrublands (Figure 5), which are only present in Castilla y León in Spain and Lazio and Puglia in the centre and southeast of Italy, respectively.

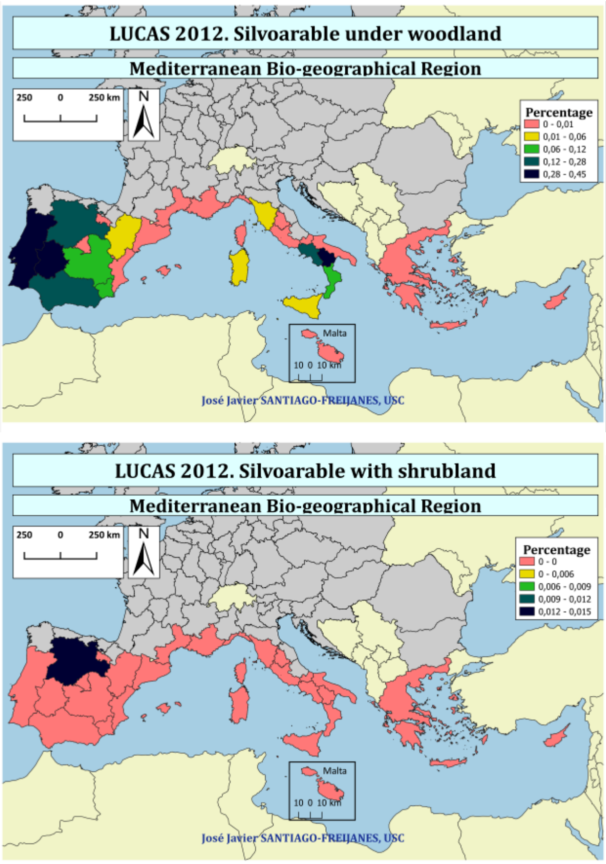

Figure 5. Percentage of silvoarable (annual crops) lands linked to woodland and shrublands in forest lands.

Policy

Figure 6 shows the number of RDP measures that promote the different types of agroforestry practices within the 2014-2020 RDPs. There are 22 RDP promoting silvoarable practices in the Mediterranean countries of Europe. However, five RDP placed in the Mediterranean area of Spain (Valencia, Aragón, Baleares, and La Rioja) and Italy (Sardegna) are not fostering silvoarable practices. Portugal uses four measures to promote silvoarable practices while only one is used in Castilla y León, Castilla la Mancha, Extremadura, Madrid, Murcia and Cataluña in Spain. In France, two measures are used to foster silvoarable practices in the Provence-Alpes-Côte d´Azur while only one is considered in Languedoc-Roussillon and Corsica. The number of measures fostering silvoarable practices in Italy goes from one to four, depending on the region, with a higher number in Molise (four measures) than in Sicilia, Basilicata, Campania, Lazio and Umbria all them with two measures.

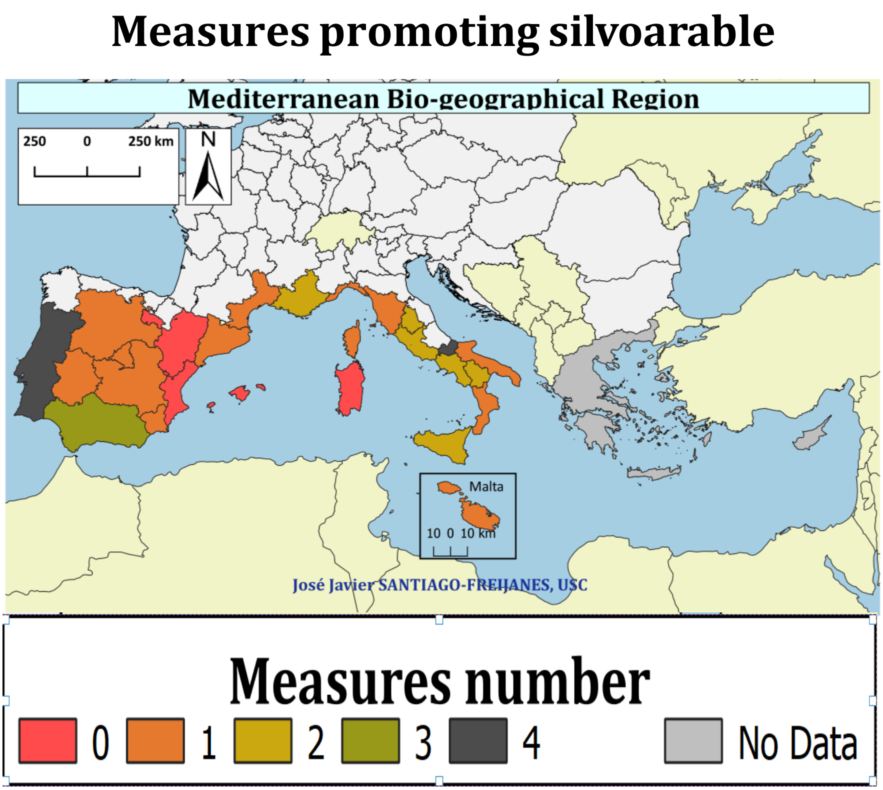

Figure 6. Number of RDP 2014-2020 measures promoting silvoarable agroforestry practices.

Country	RDP	RBS	TG	LFE	LFR	LFM	Country	RD	RBS	LFE	LFR	LFM
Spain	ES30 MADRID	8.1			8.1		Italy	ITC3 LIGURIA				
	ES41 CASTILLA Y LEÓN		10.1					ITF2 MOLISE		11.2	4.4	10.1, 12.2
	ES42 CASTILLA LA MANCHA					10.1		ITF3 CAMPANIA		4.4	4.4	4.4, 10.1
	ES43 EXTREMADURA				4.4			ITF4 PUGLIA		4.4	4.4	4.4
	ES51 CATALUÑA	10.1			10.1	10.1		ITF5 BASILICATA		4.4	4.4	10.1
	ES61 ANDALUCIA			4.4, 10.1		8.5, 10.1		ITF6 CALABRIA		4.4	4.4	4.4
	ES62 MURCIA					4.4		ITG1 SICILIA		4.4		12.1
France	FR83 CORSE					10.1		ITI1 TOSCANA	4.4	4.4	4.4	
	FR81 LANGUEDOC					10.1		ITI2 UMBRIA		4.4		12.2
	FR82 PROVENCE-ALPES			6.1		10.1		ITI4 LAZIO		4.4, 10.1	4.4	
	MALTA			10.1	10.1		Portugal	PORTUGAL	4.4, 15.1	8.2		7.4

Table 2. Riparian buffer strips management (RPB), Transhumance grazing (TG), Landscape features establishment (LFE), restoration (LFR) and maintenance (LFM) linked to silvoarable agroforestry practices per rural development program (RDP).

Table 2 shows the type of agroforestry activities promoted by the different types of measures per region to enhance the care of the water bodies through the use of woody perennials (Table 2) within the riparian buffer strips which were promoted by the measures 8.1 (Madrid), 10.1 (Cataluña) and 4.4 and 15.1 (Portugal) in the Iberian Peninsula, but also to measure 4.4 in Italy (Toscana). Especially important are those measures associated to landscape features establishment, restoration and maintenance with regard to habitat interconnections, which are promoted by 5 (measures 4.4, 6.1, 8.2, 10.1 and 11.2), 3 (measures 8.1, 4.4 and 10.1) and 6 (measures 4.4, 7.4, 8.5, 10.1, 12.1 and 12.2) different RDP measures, respectively. Landscape feature establishment is promoted through measure 4.4 in Spain (Andalucia) but mostly in Italy (Campania, Puglia, Basilicata, Calabria, Sicilia, Toscana Umbria and Lazio) while the same action is activated thanks to measure 10.1 in Andalucia, Malta and Lazio, measure 6.1 in France (Provence-Alpes) and measure 11.2 in Italy (Molise). Landscape features restoration is also promoted by measure 4.4 in Spain (Extremadura) and Italy (Molise, Campania, Puglia, Basilicata, Calabria. Lazio and Toscana) as well as by Measure 8.1 (Madrid) and measure 10.1 in Cataluña (Spain) and Malta. Finally, landscape features maintenance is paid to farmers through measure 4.4 in Spain (Murcia), Italy (Liguria, Campania, Puglia and Calabria), measure 7.4 in Portugal, measure 8.5 in Andalucia and measure 10.1 in Spain (Castilla la Mancha, Cataluña, Andalucia), France (Corse, Languedoc and Provence-Alpes), and Italy (Molise, Campania, and Basilicata). Measures 12.1 in Sicilia and 12.2 in Molise have also the target to maintain landscape features.

Country	PDR	Honey
Malta	MALTA	10.1
Portugal	PORTUGAL	8.2, 10.1
Spain	ES23 LA RIOJA	10.1, 11.1, 11.2
	ES24 ARAGON	10.1
	ES41 CASTILLA Y LEÓN	10.1
	ES42 CASTILLA LA MANCHA	10.1

Country	PDR	Honey
Spain	ES43 EXTREMADURA	10.1, 11.1, 11.2
	ES51 CATALUÑA	10.1, 11.1
	ES53 BALEARES	1.2 (DEMO)
	ES61 ANDALUCIA	10.1, 11.1, 11.2
	ES62 MURCIA	10.1
Italy	ITG2 SARDEGNA	4.1

Country	PDR	Honey
France	FR81 LANGUEDOC	10.1
	FR82 PROVENCE-ALPES	10.1

Table 3. Honey promotion per rural development program (RDP).

1.5. Discussion

Silvoarable practices extent in Europe is rather low, being mostly associated to those areas where agroforestry systems are the main type of land use such as the “montado” or “dehesa” in Portugal and western Spain. The areas of the Mediterranean with the lowest extent of agroforestry are those with the highest population density (Margaras 2019) mostly linked to Cataluña and France Mediterranean regions but also those with the lowest population density such as Aragón in Spain. This means that the intensification was higher in those highly populated areas with an excellent transport infrastructure network but also in those areas where the population change has been most negatively impacted, as farmers are key to foster agroforestry in the territory (Margaras 2019). Silvoarable systems need to be promoted as key practices in those areas with low and high population density by firstly favouring farmers quality of life and secondly by enhancing consumers quality of life and health by reducing the presence of pollutants in waters and products respectively through the adequate development of RDP measures.

The Mediterranean area of Europe is characterized by having mid mean temperatures but hot temperatures and lack of precipitation in summer which may explain the dominant vegetation in the Mediterranean area mainly associated to perennial crops either permanent grasslands or permanent crops (mostly olive groves and in some Spanish areas nut trees and/or vineyards) (EEA 2002). In the whole Mediterranean countries of Europe, only two regions in Spain have cereals (Castilla la Mancha and Castilla León) as dominant land cover. The fact that most of the regions of the Mediterranean area of Europe are dominated by perennial vegetation, including broadleaved, pine stands, shrublands and vineyards, makes silvopasture the traditional dominant type of agroforestry practice that should be used in most of the Mediterranean areas (Papanastasis 2004). Both Castilla and León and Castilla la Mancha regions, which have cereals as their predominant agricultural land use are usually linked to livestock system either because they are cropped to produce feed or because animals are usually grazing the residues. Grazing crop residues can be associated with mixed farming systems (EIP-Agri 2017) which is key to reduce the inputs on fertilizers in the farm. Europe needs to overcome the expected shortage of fertilizers in the continent, where only exists small reserves of phosphate bearing rock which induces recent price volatility - in 2008, prices of phosphorus rock rose by 700% in a little over a year, contributing to increases in fertiliser prices (EU Communication 517 2013). This can be addressed by the use of renewable resources such as woody perennials as a source of compost or biochar which may enhance soil fertility (EU 2019a/1009) in arable lands.

The presence of woody perennials in most of the Mediterranean area of Europe can be related to the fact that deep-rooted species are needed to overcome the long and dry summer that Mediterranean plants have to face (Chaves et al. 2002), but in the case of the two “Castilla” regions, this is overcome thanks to the water coming from the surrounding mountain systems. The most extended woody perennials in silvoarable practices are olive trees, which are usually intercropped by two main reasons, obtain an extra income and reduce the negative impact of soil erosion associated to those ploughed and bared soils.

Moreover, climate change adaptation can also be seen in the cereal growth period in the Mediterranean area compared with the northern European areas, as cereals are usually harvested at the end of the spring before the summer drought starts and usually sown after the first autumn rains to increase the cereal growth period in the Mediterranean areas (Pérez-Camacho et al. 2012). Both the deep-rooted perennials and the annual cereal fast-growing species can be considered as nature based climate adaptation mechanisms traditionally existing in this part of Europe where precipitation intra-annual variability is so frequent and that will be exacerbated by climate change (IPCC 2013). The introduction of deep-rooted perennials can be seen as an agroforestry practice that may be further considered for arable farming systems in northern European latitudes to overcome changing and warming effects of climate change. This is one of the recommendations of the European Commission EU as part of the indicative measures that may be included in the information on LULUCF actions submitted pursuant to Article 10(2)(d) (Decision 529/2013/EU) that can be related to agroforestry.

The CAP direct payments to agricultural areas in Europe depend on two predominant types of land use: arable, and permanent crops (orchards) besides permanent grasslands, while Rural Development Programmes aims at enhancing the production of ecosystem services related with the environment. Therefore, large areas of cereals, as well as fruit trees, should be predominantly paid to integrate silvoarable practices. Currently, silvoarable practices are mostly linked to Lucerne and not to dominant cereal production. Lucerne is a perennial legume crop with important root systems and aboveground biomass, which enriches the system in organic matter and physical properties of the soil such as structure, water infiltration and retention and enhances microbial activity, being this useful as such, as part of a rotation, or by itself for the olive tree (Wezel et al. 2014). The promotion of silvoarable practices through the introduction of trees/shrubs in cereal areas will be able to overcome extreme heats and lack of water. Landscape features such as trees in a row, hedgerows and isolated trees are the main form to promote silvoarable practices in Europe. These landscape features will reduce the impact of climate change effects such as prevalent winds, extreme heats and heavy rains but will also increase the provision of ecosystem services such as pollination while improving soil health by increasing soil organic matter (Torralba et al. 2016) as it is currently promoted by measure 10.1 with a very limited budget. Poplar is an adequate tree to introduce in these cropland dominated Spanish areas and in other areas of Europe (Kachova and Ferezliev, 2020; Paris et al. 2019) due to its adaptability to these soils and environmental conditions (Isebrands and Richardson 2014), its capacity of being used as part of the riparian buffer strips but also because there is an excellent industry demanding, processing and marketing this type of fast-growing tree species all over the world such as GARNICA.

Other species such as cypresses may play a role, as the form of this tree reduces the effect of shading on crops. However, opposite to poplar, adequate cypresses value chains should be encouraged and developed (Papanastasis et al. 2008) within the current bioeconomy framework. On the other hand, in those areas where extreme heats are becoming more frequent, cereal variety selection to shade and some degree of shading may be useful. The use of some kind of shadow in cereal production has shown the reduction of weeds, and therefore associated pesticides use, as annual herbaceous weed species are more initially light-demanding than the cereal crops. The shadow favoured a better instalment of the cereal crop because reduces the competition with the light-demanding annual weed species that at the end makes the cereal to produce better for the reduced competition with the weeds when compared with the cereal production in open sites. The role of silvoarable practices is recognized in most of the RDP of the Mediterranean basin where landscape features associated to establishment, maintenance and restoration in Italy, restoration and management in Spain and Management in France, are promoted through different measures. The longer tradition of France using landscape features (Mosquera-Losada et al. 2018) makes less relevant the restoration and establishment measures but highly relevant their maintenance. Measure 4.4 associated to the investments in physical assets is mostly used to establish or restore already existing landscape features (i.e. copses, hedgerows, trees in line….) while the agri-environment measure 10.1 is mostly linked to the maintenance of these landscape features, mainly because of the recognition of the ecosystem services they deliver (water, erosion…).

The link of silvoarable practices with both olive and oak trees is related to the traditional management of these areas to prevent soil erosion and enhance nutrient cycling in the case of olive trees. Besides these benefits, the provision of feed to livestock associated to the acorns delivered by oaks makes the establishment of silvoarable measures crucial in areas like Portugal and Andalucía, where mixed farming systems are key to foster the economy of the area.

Despite the benefits and the promotion of silvoarable practices in Europe, the extent of this type of land use is indeed low. Technical knowledge already existing in research should be transferred to farmers to promote silvoarable practices in Europe as claimed in the AFINET project (2020) by over 900 stakeholders. Therefore, funds to promote extension services, demonstration fields and living labs are essential to foster the transition from intensive to extensive livestock systems as highlights the policy report of AFINET (2020). Moreover, intensive farming systems are based on the decapitalization of soils and extensive use of resources mostly produced far away from agricultural lands where it is used, which implies a large use of non-renewable energy. On the opposite, cropland farming systems based on silvoarable practices capitalize the soil, as organic matter is introduced in deeper soil layers and nutrients are recycled thanks to the deep roots of the trees and shrubs (Mosquera-Losada et al. 2011, 2015). The decomposition of these roots in deeper soil layers prevents from organic matter mineralization when ploughing is performed, being also a good way to comply with sustainable initiatives such as the "4 per 1000" initiative (Four per thousand 2020). Agroforestry provides nature-based solutions to recover degraded soils that were not sustainably used, which is an opportunity to be explored in the next CAP. The introduction of animals, grazing the residues of those crops linked to arable lands, may have also delivered benefits in the surrounding areas through the promotion of mixed farming systems (EIP-Agri 2017).

Agroforestry can be interpreted as a land use practice but also as a farm and landscape system as it may favour the integration of different land uses in the Mediterranean area where vegetation growth rate is slow. The use of hedgerow biomass residues as a source of organic matter in arable soils is key to increase the natural capital resource of the soils in the agricultural lands. Moreover, the reduced natural productivity per unit of land of agricultural lands in the Mediterranean areas that are usually associated to a larger size of the farms can be overcome if the delivery of more products per unit of land is promoted based on an adequate integration of woody perennials that enhance nutrient recycling associated to organic matter. However, the adequate promotion of value chains is needed based on the increase of alternative uses of the woody component that nowadays are not used at all and in the adequate establishment of value chains within the updated bioeconomy European strategy (EC 2018). This should be enhanced through the adequate provision of initial infrastructures based on the business plans development, but also in the establishment of adequate extension services able to promote these alternatives that are more linked to the environment preservation.

There were no measures linked to the bioeconomy of the woody perennials associated with silvoarable practices in Europe. The current CAP is based on the promotion of activities associated to the introduction, restoration and maintenance of woody perennials (landscape features) in arable lands to enhance the environment deliveries (Mosquera-Losada et al. 2018a, 2018b; Santiago-Freijanes 2018a, 2018b, 2018c) but should be integrated with measures associated to social aspects related to bioeconomy promotion through the farmers cooperativism enhancement, but also to the adequate development of value chains of the multiple products considering life cycle assessments that promotes the reduction of the use of non-renewable energy resources. CAP promotion should take into account that public and private areas as public lands are not able to receive CAP direct payments.

1.6. Conclusions

The reduced extent of silvoarable agroforestry practices delivering ecosystem services in the Mediterranean area of Europe is enormous because of the reduced currently extent that this sustainable land use system has. Silvoarable practices should be promoted by the CAP considering the promotion of the extension services activities but also the development of adequate supply and value chains within The Farm to Fork and EU Bioeconomy Strategy to fulfil the European Green Deal promoted by the European Commission.

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Chapter 2. Agroforestry policy promotion in Grassland Mediterranean areas

1.1. Abstract

Silvopasture is the deliberate integration of a woody component with grazed pastures as understorey. It is one of the most extended agroforestry practices all over the world. The silvopasture use is key to increase the sustainability of livestock farming systems as this agroforestry practice reduces the use of concentrates since the woody component provides feed for animals. However, it is not an extensively used practice in Europe, This paper aims at evaluating the current situation of permanent grasslands in the Mediterranean area of Europe as well as the rural development programmes fostering silvopasture to better understand how sustainable land use systems are promoted and provide insights to foster silvopasture across Europe. Most of the silvopasture measures related with silvopasture are adapted to the local necessity, mainly associated to regeneration and maintenance in the managed dehesas but linked to forest fire prevention through silvopasture promotion in the majority of the Mediterranean regions of Europe.

1.2. Introduction

Agriculture in Europe is strongly driven by the Common Agricultural Policy which establishes a set of rules for the 28 countries included in the European Union. The CAP consists in two Pillars, the pillar I (Regulation 1307/2013) where farmers get direct payments based on the surface they have and Pillar II (Regulation 1305/2013) which is more linked with the environment. Up to now, the European Union provides the general rules for EU Member States to fund sustainable farming through direct payments across Europe. However, the rules of the Pillar II are usually provided by the Member States to foster sustainable practices according to the different European Union biogeographic regions and locally adapt these practices to increase the ecosystem service delivery (EAA 2017). The next CAP 2021-2027 should fulfil 9 objectives (EU 2019b) directly related to the three sustainable aims of the United Nations: economic, environment and social. The CAP 2021-2027 also recognizes the need for providing sustainable practices that should be adapted at the national level. Therefore, there will not be EU general rules with regard to land use for farmers to get direct payments. Instead, Member States should fulfil the 9 main aims of the CAP and different types of EU strategies (bioeconomy, farm to fork, green deal…) by demonstrating results linked to key actions such as biodiversity, nutrient efficiency or climate mitigation.

Grasslands area is one of the most important types of land use in Europe, where, attending to EUROSTAT (2020) represents the 50.5 and 18.8% of the whole and agricultural land in Europe (EU-28), respectively. Permanent grassland is usually associated with a permanent soil cover with an important internal dynamic from an ecosystem point of view. Compared with arable lands, grassland areas are able to sequester more carbon, increase biodiversity or reduce soil erosion (Bengtsson et al. 2019). Permanent grassland definition has been recently modified from a policy perspective. Thus, in the CAP 2007-2013 only herbaceous vegetation was considered as part of the permanent grassland, while in the current CAP (2014-2020) the presence of woody perennials is considered as part of permanent grasslands as a source to feed animals, which turns grasslands with woody perennials eligible to get direct payments in the current 2014-2020 CAP (Regulation 1307/2013) by farmers. Woody perennials are especially relevant in the Mediterranean area of Europe, where herbaceous vegetation is not able to survive during the long summer period, which makes them essential to sustain livestock systems avoiding a huge dependence of external inputs. However, woody perennials are able to survive these restricted weather periods due to their deep root systems. Moreover, due to the importance of grassland areas as a source of ecosystem services (Bengtsson et al. 2019), the European Commission included the preservation of this type of land use at the national level as part of the greening (Regulation 1307/2013) while it is part of different programmes of the CAP in the Rural Development Programmes (RDP). If woody perennials are included, permanent grasslands are called silvopasture (Mosquera-Losada et al. 2018), a type of agroforestry systems able to foster sustainability in rural areas (Mosquera-Losada and Prabhu 2019). There are 118 RDP in the whole 28 member states, out of which 29 are included in the Mediterranean area of Europe. The Mediterranean area of Europe is one of the most vulnerable regions in the world to the impacts of global warming (IPCC 2013), which makes necessary to provide policy tools to foster sustainable land use systems in this region of Europe. This paper aims at evaluating the current situation of permanent grasslands in the Mediterranean area of Europe as well as the rural development programmes fostering silvopasture to better understand how sustainable land use systems are promoted and provide insights to foster silvopasture across Europe.

1.3. Material and methods

Results will be presented taking into account the main indicators that affect productivity and may modify the implementation of policies attending to the social (land ownership as an indicator of evaluating long-term practices and as a restriction to receive CAP payment), geographic (altitude as an indicator of environment constraints), biological (vegetation and agroforestry practices distribution) and policy (rural development policies that are developed at regional level by each member state) that can be related to the promotion of farming systems to fulfil the main pillars of the CAP: social, economic and environmental aspects.

LUCAS analysis

The form of how silvopasture extent is estimated is described in Table 1 (Mosquera-Losada et al. 2018). In this study, The "Land use/cover area frame statistical survey", abbreviated as LUCAS was used to identify silvopasture (EUROSTAT 2016; Mosquera-Losada et al. 2018). Eurostat has the LUCAS survey micro-data collection of cover and land use which is freely available on the LUCAS website (EUROSTAT 2013). For this study, we used the LUCAS 2012 data, when Croatia was not part of the EU, so the results are only referred to the EU27.

LUCAS is a two-stage sample survey. The first phase is a systematic sampling carried out in around 1.1 million points (spaced 2 km). In a second stage, a representative subset of 270,267 points was selected to be physically visited by inspectors.

Table 1. Criteria used for identifying the agroforestry practices.

Land cover / variable	Code	LUCAS class	Silvopast AGF
Grassland	E10	Grassland with sparse tree/shrub cover	LC2
	E20	Grassland without tree/shrub cover	LC2
	E30	Spontaneously re-vegetated surfaces	LC2
Woodland	C10	Broadleaved woodland	LC1
	C21	Spruce dominated woodland	LC1
	C22	Pine dominated woodland	LC1
	C23	Other coniferous woodland	LC1
	C31	Spruce dominated mixed woodland	LC1
	C32	Pine dominated mixed woodland	LC1
	C33	Other mixed woodland	LC1
Permanent industrial crops	B84k	Mulberries and carob	LC1
	B84m	Willow	LC1
Shrubland	D10	Shrubland with sparse tree cover	LC1
	D20	Shrubland without tree cover	LC1
Grassland	E10	Grassland with sparse tree cover	LC1
Land management	1	Signs of grazing	Yes

LC1 = Primary land cover
LC2 = Secondary land cover

LUCAS uses a double classification system for land covers that also includes the land use with multiple layers, used only for specific landscapes, such as agroforestry and complex or heterogeneous area. For example, in silvopasture, a woody vegetation layer (LC1) is typically accompanied by the secondary layer (LC2) composed of grass. Another useful variable included in the LUCAS database is land management, which contains information if there are signs of grazing or not, which therefore identify silvopasture. By using LUCAS data we distinguish silvopasture in arable crops (temporary grassland) which are grazed, silvopasture with orchards and silvopasture within forestland.

To estimate the extent of agroforestry of silvopasture in hectares at RDP region level, we divided the number of points coded as silvopasture in each territory by the total number of LUCAS points in this territory and multiplied this by the surface of the territory (Mosquera-Losada et al. 2018).

Policy analysis

The policy analysis was conducted considering the measures activated by the Pillar II of the CAP (EU 2013) related to the RDPs, as carried out by Mosquera-Losada et al. (2018). A policy analysis evaluating the promotion of agroforestry practices was developed in the deployment of the 29 Rural Development Programs of the Mediterranean area of Europe in the period 2014-2020 available on the internet (EC 2019) and excluding Cyprus and Greece. In this study, data from Pulla et al. (2013) for the forest ownership and from EEA (2017) for the altitude were used. We evaluated measures associated with agriculture (grazed temporary grassland and orchards) and forest land (usually linked to forest fire risk reduction).

Upscaling

The obtained geographical indicators from LUCAS (percentage and number of hectares), as well as the policy indicators (activated measures), were upscaled and mapped per region of Europe by using QGIS 2.18. Both forest ownership and altitude have been processed with QGIS 2.18.

1.4. Results

Social context: the ownership

The type of ownership of forest lands in the Mediterranean Region of Europe is mostly private. Regions like those linked to Continent Portugal, Catalunya and Extremadura in Spain as well as those like Liguria and Toscana in Italy, have more than 77% of the forest land privately owned.

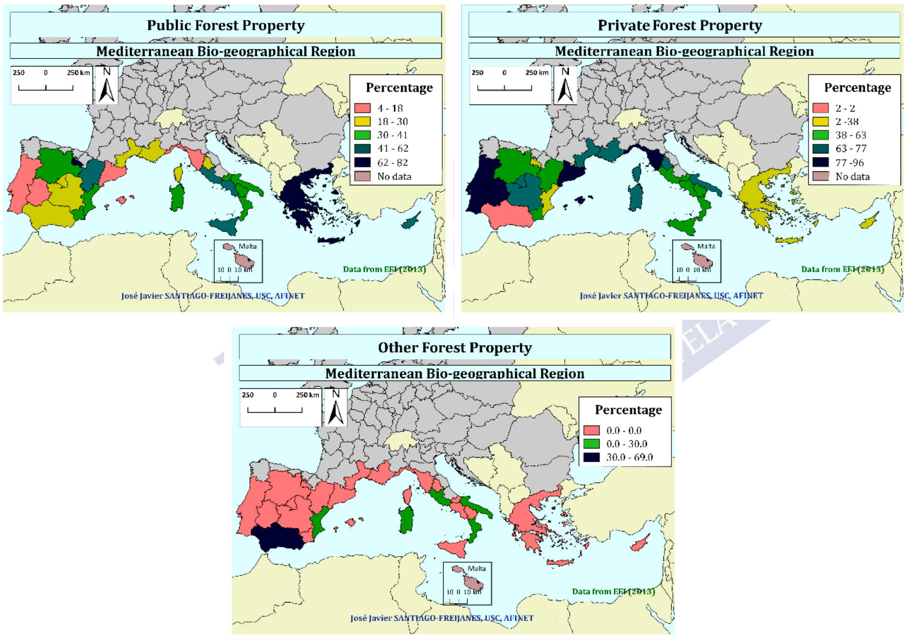

Figure 1. Type of dominant property in the European lands as private, public and other forest property (identified as not classified ownership in Italy and unknown or unclear ownership) (data from Pulla et al. (2013)).

Other regions placed in Spain have over 30% of public forest (Castilla y León, Aragón, Valencia, Murcia, La Rioja) as happens in Greece, and most of the Mediterranean Regions of Italy excluding Toscana, Umbria and Sardegna. Only Andalucía has over 30% of the properties associated to "other forest property" being also present at some extent in Italy (Sicilia, Lazio, Puglia and Calabria) and some other areas of Spain (Valencia). The categorization of other forest ownership depends on each EU Member State, which makes difficult to have a clear comparison of their meaning, but they are usually areas that cannot be categorized either as public or as private.

Geographic context

Figure 2 shows the mean, maximum and minimum altitude of the Mediterranean regions basin. High mountains areas are mainly placed in Spain (Andalucía and Aragón), France (Provence-Alpes-Côte d'Azur) and Italian (Sicilia). The maximum mean altitude is observed in the Central Spanish plateau, and France (Provence-Alpes-Côte d'Azur). The lowest mean altitude is found in most of the Mediterranean countries with the exception of the Spanish Plateau.

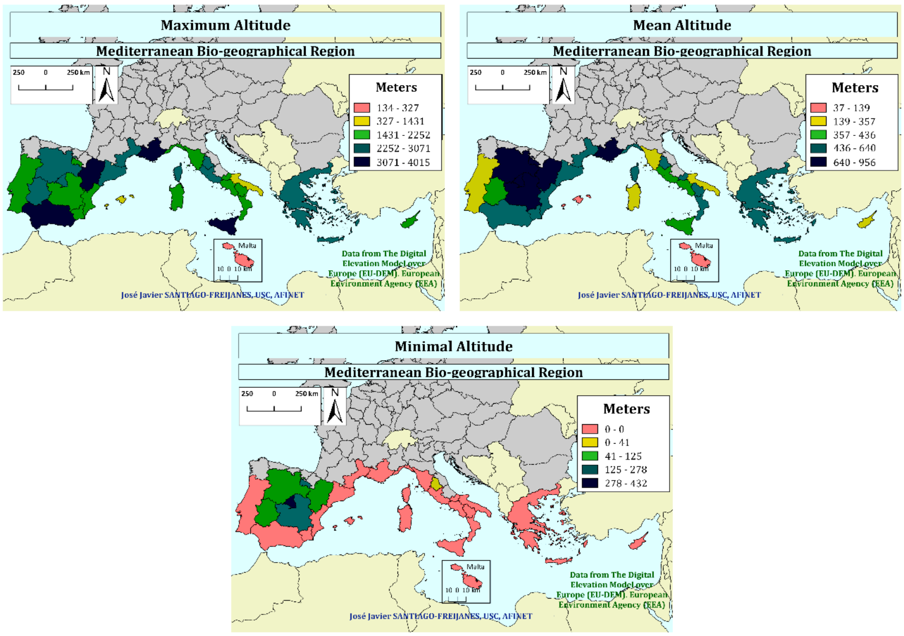

Figure 2. Maximum, mean and minimum altitude (m asl) of the European Mediterranean regions basin (Data from EEA (2017)).

Mediterranean agriculture and woodland

Figure 3 shows the dominant type of land cover in the regions of the Mediterranean area of Europe. Grassland without tree/shrub cover is the dominant land cover in Sicilia, an area with a high altitude. The rest of the regions are mainly dominated by woody vegetation such as grassland with sparse tree/shrub cover (Madrid), olive groves (Andalucía), shrublands without tree cover (Aragón and Malta) and broadleaved woodlands. Pine dominated conifer land use is mainly placed in Valencia, Murcia and Cyprus.

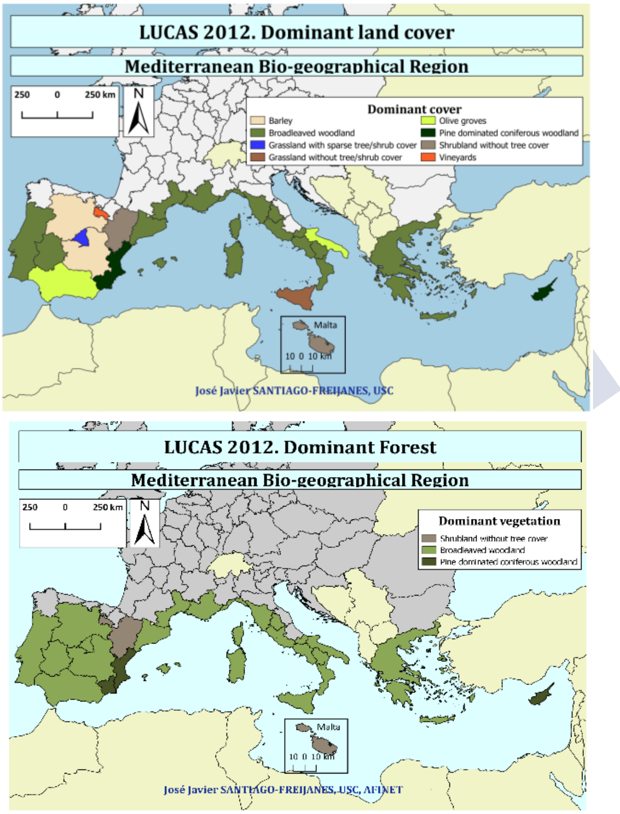

Figure 3. Share of dominant land cover, in the Mediterranean Regions of Europe.

If the forestland use is considered (Figure 3), most of the European Mediterranean area is dominated by broadleaved woodlands. Murcia and Valencia regions in Spain, together with Cyprus, are associated with Pinus dominated coniferous woodland. Regions with a high proportion of public property such as La Rioja and Aragón in Spain and Malta are mainly associated with shrubland without tree cover. However, the size of the shrubs and the trees may vary a lot and sometimes it is difficult to establish a clear criterion to easily distinguish these two types of vegetation due to the different definitions among countries.

Mediterranean agroforestry

Silvopasture is the most important agroforestry practice in Europe, reaching up to 37% of the land in some regions of Europe (Figure 4). Silvopasture is mainly located in Extremadura, La Rioja, Baleares and Andalucia in Spain, Sardegna and Basilicata in Italy besides Portugal and Greece. On the contrary, the Spanish regions of Murcia and Valencia in Spain, Toscana and Molise in Italy, as well as Malta, have the lowest share of silvopasture in the Mediterranean area of Europe.

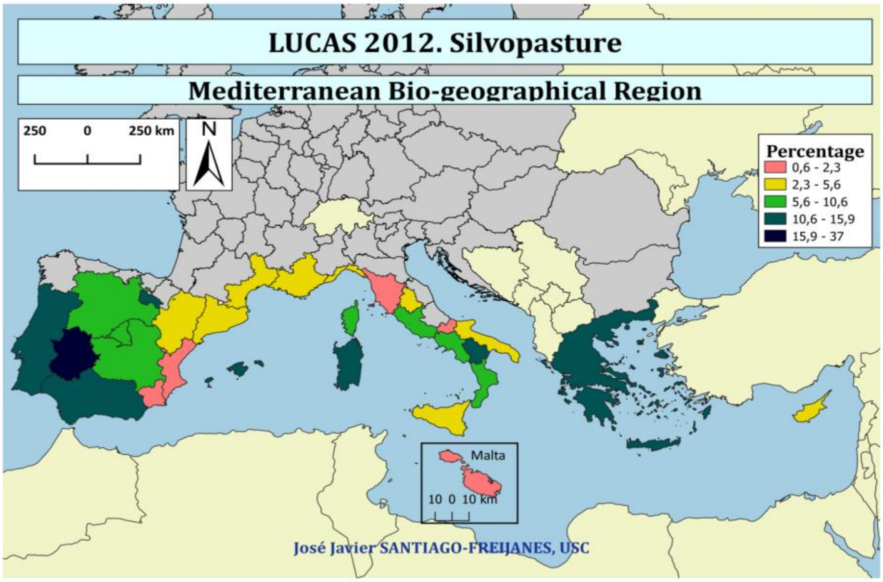

Figure 4. Percentage of land occupied by silvopasture.

Silvopasture can be part of agricultural lands as well as forestlands mainly dominated by woodlands or shrublands as shown in Figure 5. Pasture linked to permanent crops are dominant in Baleares and Andalucia with a high share of olive trees, but also in Portugal and Lazio in Italy. However, when silvopasture linked to no fruit trees is joined to those linked to fruit trees, is Extremadura, Madrid, Baleares in Spain and Basilicata and Sardegna in Italy, as well as Greece the ones with the higher share or silvopasture in agricultural lands.

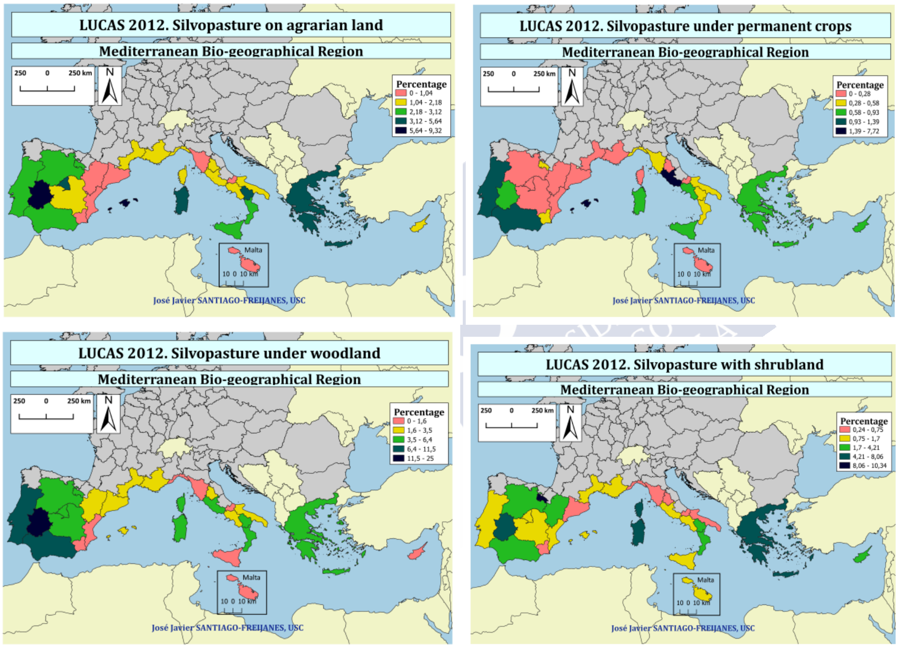

Figure 5. Percentage of silvopasture (pasture) in agrarian lands (the sum of (i) pastures with non permanent crop trees and grazed pasture as understory and (ii) permanent crop (fruit + nut) trees and grazed pasture as understory), and lands linked to woodland and shrublands.

Pasture under shrubland is mainly associated to La Rioja, the Spanish Dehesa (Extremadura), Sardegna (Italy), Corsica (France) and Greece followed by some regions of Italy (Lazio, Basilicata and Calabria), Spain (Andalucia, Castilla y León, and Aragón). When silvopasture linked to woodlands is evaluated, Extremadura but also Andalucia and

Portugal, the places with the largest share of the Iberian present the highest share, followed by Castilla León, Madrid, La Rioja and Castilla la Mancha in Spain, Corsica in France, Sardegna, Basilicata, Calabria and Lazio in Italy and also Greece.

Policy

Figure 6 shows the number of RDP measures that promote the different types of silvopasture within the 2014-2020 RDPs in both agricultural and forest lands. Regarding the number of measures promoting silvopasture with temporary grassland (arable lands), there are nine regions not promoting silvopasture (Figure 6). Most of the Mediterranean regions promote silvopasture with one measure, while Andalucia uses seven measures and Sicilia uses five. Four measures are implemented in Umbria and three in Madrid and Extremadura, in Spain, and Portugal.

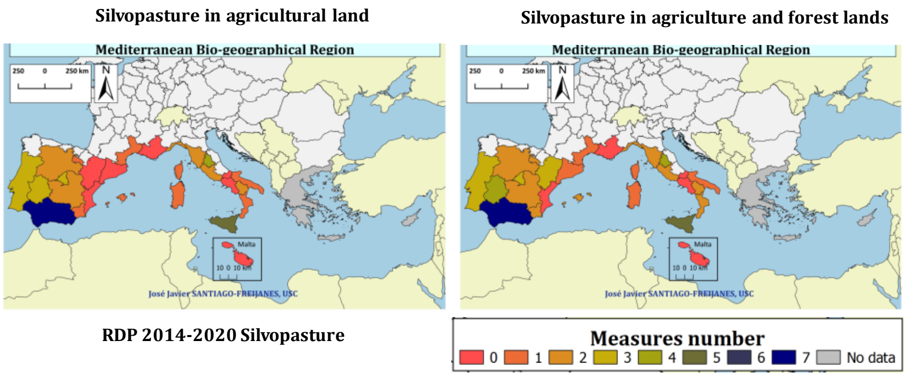

Figure 6. Number of RDP 2014-2020 measures promoting silvopasture with annual cropland forest farming

Table 2 shows the type of silvopasture measures per region to improve silvopasture management, establishment and improvement. Agroforestry education is promoted through measures 1.2 with the establishment of demo sites and with measures 2.1 and 2.3 by fostering farmers and advisors knowledge about agroforestry in the Andalucia RDP. Silvopasture is also promoted with Measures 4.1, 4.3 and 4.4

through the development of investments in physical assets such as regeneration in five Spanish RDPs. Moreover, silvopasture is also promoted in forest areas by the agroforestry measure 8.2 itself, aiming at establishing and improve silvopasture management in Portugal, two Spanish RDPs (Andalucia and Extremadura), and three Italian RDPs (Puglia and Basilicata). Silvopasture establishment and improvement is also carried out by measure 8.3 (Castilla and León) to reduce fire risk, 8.5 (Basilicata, Toscana and Lazio) to improve the forest resilience and 8.6 (Toscana and Umbria) to mobilize silvopasture products. Silvopasture is also enhanced by measures 12.1 to improve Nature 2000 areas and 15.2 to preserve forest areas. Agri-environment measure 10.1 is deployed to improve silvopasture management and establishment in the rural development programs of Spain (La Rioja, Madrid, Andalucia), France (Corse), Italy (Sardegna, Lazio) and Portugal, but also in Castilla la Mancha through the promotion of grazing with landscape features. Silvopasture is also supported with permanent crops, namely, orchards through measure 10.1 in Spain (Castilla y León), France (Languedoc), Italy (Liguria, Calabria, Sicilia) and Portugal, but also through measures 8.6 and 11.1 in Italy (Toscana and Sicilia).

Table 2. Measures favouring silvopasture combined with woody perennials and orchards. Reg: regeneration.

Country	RDP	silvopasture	Orchard silvopasture	Country	RDP	silvopasture management, establishment and improvement	Orchard silvopature
Portugal	PORTUGAL	8.2, 10.1	10.1	Italy	ITC3 LIGURIA	12.2	10.1
Greece	GREECE				IFF4 PUGLIA	8.2	
Spain	ES23 LA RIOJA	10.1			ITF5 BASILICATA	8.2, 8.5	
	ES30 MADRID	4.4, 8.3, 10.1			ITF6 CALABRIA		10.1
	ES41 CASTILLA Y LEÓN	8.3	10.1		ITG1 SICILIA	8.3, 8.4, 8.5	10.1, 11.1
	ES42 CASTILLA LA MANCHA	4.3, 10.1 (LF)			ITG2 SARDEGNA	10.1	
	ES43 EXTREMADURA	4.3, 4.4 (reg), 8.2 (reg)			ITI1 TOSCANA	8.5, 8.6	8.6
	ES61 ANDALUCIA	1.2 (demo), 2.1(farmers assessment), 2.3 (advisor assessment), 4.1, 4.4 (reg), 8.2, 10.1			ITI2 UMBRIA	8.2, 8.6, 12.1, 15.2	
	ES62 MURCIA	4.1					
	ES63 BALEARES	1.2 Demo			ITI4 LAZIO	8.5, 10.1	
France	FR83 CORSE	10.1					
	FR81 LANGUEDOC		10.1				

One of the most important aspects to foster agroforestry is the development of management plans (Table 3) in general, as promoted by measure 11.2 in La Rioja or measures 8.1 and 8.4 in Aragón. Also, management plans focused on (i) risk prevention as carried out in Spain by measures 8.1 and 1.2 in Extremadura and Andalucía, respectively, and by measure 8.3 in Spain (Aragón, Madrid, Cataluña and Murcia) and Italy (Sicilia) (ii) restoration fostered by measures 8.3 in Spain (Baleares), Italy (Calabria) and Portugal, and 8.4 in Spain (Aragón) and Italy (Sicilia) and (iii) disaster prevention developed by measure 8.3 in Aragón.

Table 3. Woodland production through the development of forestry technologies, processing, mobilising and marketing of forest products as well the value chain per rural development program (RDP).

		AF management plans				No Timber Woodland Products		
Country	RDP	General	Forest fire prevention	Forest restoration	Country	RDP	NTWP value chain	NTWP production
Spain	ES23 LA RIOJA	11.2			Spain	ES23 LA RIOJA		8.6
	ES24 ARAGON	8.1, 8.4	8.3	8.4		ES42 CASTILLA LA MANCHA	9.1	
	ES30 MADRID		8.3			ES52 VALENCIA	8.6	
	ES43 EXTREMADURA		8.1			ES43 EXTREMADURA		8.6
	ES61 ANDALUCIA		1.2			ES61 ANDALUCIA	1.2	1.2, 8.6
	ES53 BALEARES			8.3				
	ES51 CATALUÑA		8.3					
	ES62 MURCIA		8.3		Italy	ITF3 CAMPANIA	4.1	
Italy	ITF6 CALABRIA			8.3		ITG2 SARDEGNA	8.6	
	ITG1 SICILIA		8.3	8.4		ITI2 UMBRIA	8.6	
Portugal	PORTUGAL			8.3	Portugal	PORTUGAL	4.2	8.6

Both no timber woodland production through the development of forestry technologies, processing, mobilising and marketing of forest products, as well as the development of the value chain are key to increase diversification and income for farmers from forestlands (Table 3). The forestry technologies related to processing, mobilising and marketing of forest products are mostly fostered through measure 8.6 in Spain (La Rioja, Extremadura and Andalucia which also uses M1.2) and Portugal. Value chain improvement is key to foster agroforestry associated to forest lands as recognized in Spain (La Rioja and Valencia through measure M8.6, Castilla la Mancha (M9.1) and Andalucia (M1.2)), Italy (Campania (M4.1) and Sardegna and Umbria through measure 8.6) and Portugal by financing investments (M4.2).

1.5. Discussion

The Mediterranean area of Europe is characterized by mild temperatures on winter but hot temperatures and lack of precipitation in summer, which may explain perennial crops as permanent grasslands or permanent crops (mostly olive groves and in some Spanish areas nut trees and/or vineyards) are the dominant vegetation in this area. Depending on the woody perennials, silvopasture could be related to forestlands (oaklands, shrublands and pine stands) or agricultural lands (low tree density or permanent crops (e.g. fruit trees). The dominant woody perennial vegetation delineates the first framework for the development of the silvopasture agroforestry systems. Silvopasture implementation is a type of seminatural system where management by man delineates the landscape layout of the system. Anthropogenic pressure, linked to intense pastoral and arable activities in Mediterranean forest, caused a reduction on pine-oak forests in the Mediterranean area for centuries (Gassner et al. 2020), being this reduction more intense in the second half of the XXth century. Afterwards, land abandonment and the European Union and National policies linked to both reforestation and afforestation (Santiago-Freijanes et al. 2018) have increased the proportion of forestlands as the dominant vegetation in most Mediterranean regions. Moreover, farm abandonment in the Mediterranean areas associated to land degradation, water scarcity linked to climate change, and depopulation associated to migration from rural to urban areas have caused a natural expansion of forestlands in most of the European regions of the Mediterranean area (Perevolotsky and Sheffer 2011 and Vayreda et al. 2013) leading to a rise on forest fires (Alexandrian and Esnault, 2000; Plana et al. 2016). In the west part of the Mediterranean area of Europe, there are also well-managed oaklands dominating some landscape regions as part of the most important agroforestry system associated to livestock production: the dehesa recognized as an example of land use sustainability and a hotspot of biodiversity and resilience with, for example, a low forest fire risk. The profitability and the high number of ecosystem services of the dehesa/montado make both Portugal and Extremadura areas with the lowest share of public ownership of oaklands in Europe (Moreno et al. 2018). This low public ownership of oaklands also occurs in the North of Spain (Cataluña) as well as French Mediterranean regions due to the high population density they have and the negative impact that anthropogenic pressure causes on land use through the implementation of agriculture in the Mediterranean ecosystem. The dehesa area has the largest share of silvopasture of the Mediterranean region linked to agricultural land including permanent crops and also to forest lands where grazing is part of the shrublands and woodlands. The large share of agroforestry in the dehesa systems makes the number of policy measures associated with this land use very high compared with most of the regions in the Mediterranean part of Europe. Measures linked to dehesas are associated to dehesa regeneration in forest and agricultural lands due to the age of the trees which are several centuries old but also to the lack of regeneration associated to inadequate grazing management and climate change (Moral et al. 2014; Fernández-Habas et al. 2019; Rolo et al. 2012, 2013) which is currently causing huge mortality in oaks. The protection of dehesas in Spain and Portugal makes also important the policy support associated with the agri-environmental measures due to the ecosystem services dehesas deliver (Howlett et al. 2011). The dehesa agroforestry system has already developed an excellent supply chain strategy linked to the "Iberian pig", which makes value chain measures not relevant in this part of the Mediterranean area of Europe being mostly linked to other non-timber woodland production in both Portugal and Extremadura to increase the multiple-use and products obtained from the system (e.g. mushrooms, honey…).

Opposite to the well designed and managed dehesa systems, adapted to the Mediterranean weather conditions, there are other areas with high anthropogenic pressure in the past reflecting a high degree of degradation in some regions (Perevolotsky and Sheffer 2011 and Vayreda et al. 2013). These degraded areas were mostly reforested by using pioneer tree species such as pine to protect the soil from erosion, as happened in Murcia, Valencia and Cyprus areas currently dominated by pine species with a low rate of silvopasture implementation. The presence of conifer plantations in these areas is usually linked to marginal, degraded and high altitude areas and very poor soils. Conifers provide a higher level of carbon sequestration than agricultural lands (Durán Zuazo et al. 2014) but less benefit for silvopasture practices than oaklands due to the less shade (animal welfare) and feed resources (acorns) that pines provide compared to oaks (Papanastasis et al. 1995). Pine plantations are more sensitive to drought stress (Gea-Izquierdo et al. 2019) and provide fewer ecosystem services (da Silva et al. 2019) than oaklands. Oaklands are extensively dominating the Mediterranean area of Europe where the number of agroforestry measures is small. As mentioned, land abandonment caused an oakland expansion in most of the European regions prone to be fired in Mediterranean weather conditions (Perevolotsky and Sheffer 2011 and Vayreda et al. 2013). This justifies the large number of regions implementing silvopasture through the forest policy measure 8.3 associated with forest fires fighting aiming at reducing the understory as a forest fuel. Some regions also implement measures associated with forest restoration after fires happened. Silvopasture and forest farming promotion in Mediterranean areas should be based on good agroforestry management plans founded on the local conditions, but also the improvement of the production and resilience and the promotion of value chains as challenges highlighted by the 900 stakeholders participating the EU thematic network Agroforestry Innovation Network Project (AFINET 2018). Most of the Italian and French regions present a shortage on agroforestry practices linked to silvopasture, except for Calabria and Basilicata, where agroforestry is promoted by the introduction of agroforestry systems as part of the measures 8.2 and 9.5. Despite the low share of silvopasture in woodlands and shrublands of the French and Italian regions, compared with other regions of the Mediterranean area of Europe, most of the regions have measures linked to the establishment and maintenance of different forms of silvopasture in forest areas but also associated to the development of value chains as in Umbria and Sardegna regions. Greece is one of the regions with a large share of grazed shrublands, probably because shrubs fit as a source of feed for the largest density of goats of the European countries (Papachristou 2000).

Aragón, Malta and La Rioja are the three regions with a land cover dominated by unmanaged shrublands, as the share of silvopasture is rather low but higher than in other areas of Europe not dominated by shrublands. Unmanaged shrublands are transformed into forests (Perevolotsky and Sheffer 2011 and Vayreda et al. 2013) while fired forests are usually transformed in open shrublands (Baudena et al. 2020). This promotes that only La Rioja has allocated measures to improve the production of no timber woodland products and the Agri-environment measure to protect these systems. Silvopasture linked to permanent crops is indeed relevant in areas where olive trees represent a large share of the region such as Andalucia and Puglia, but also Portugal, Basilicata and Lazio. The importance of agroforestry practices within the olive orchards is linked to the intensive farming system they have suffered in the last decades with important soil erosion and degradation that can be recovered by sowing pasture under the olive trees. Furthermore, livestock grazing increases the preservation of the olive soil stands as a sustainable way to reduce competition with trees while favouring nutrient recycling through faeces and urine deposition. Andalucia has devoted measures to increase farmers knowledge on silvopasture systems, with both permanent crops and woodlands (to reduce forest fire risk), through the implementation of measures related with demo sites and farmers and advisor assessment, as highlights the EIP-Agri (2017) innovation development schemes. The establishment of agroforestry demo-sites linked to the RDP was also implemented by the Baleares Islands region, where nut trees are dominant.

Mediterranean islands acknowledge a different share of land use cover, from those with a high anthropogenic impact (Sicily) to those with lower impact (Sardegna or Corsica). Sicily is closer to the continent than the other Mediterranean islands (Ruhl 2011) and presents a long tradition of olive trees agroforestry, declining nowadays due to the land abandonment (Rühl 2011). However, it is currently still possible to find agroforestry areas as traditional cultural landscapes (Cullota and Barbera 2011). On the contrary Sardinia, with less anthropogenic impact linked to a lower population density and connectivity with the continent, managed to maintain traditional silvopasture practices linked to biodiversity hotspot of this island. Land abandonment in the last decades (Puddu et al. 2012) has conducted to a clear reduction of silvopasture practices and an increase in forest lands. Similarly, still some agroforestry and an increase of forest lands can be found in Corsica (Vella et al. 2019), Cyprus (Hellicar et al. 2019) and Baleares especially linked to nut production. Agroforestry policy measures in the Mediterranean areas are associated to demo sites and forest prevention techniques in Baleares, and forest and agri-environment measures in Sicilia and Sardegna. Value chain promotion is activated as an RDP measure in Sardegna.

The presence of woody perennials in most of the Mediterranean area of Europe can be related to the fact that deep-rooted species are needed to overcome the long and dry summer that Mediterranean plants have to face (Chaves et al. 2002) while providing feed to animals in silvopasture systems. Both the deep-rooted perennials and the sward annual species of the permanent grasslands can be considered as climate adaptation mechanisms traditionally existing in this part of Europe where precipitation intra-annual variability is so frequent (Pardini et al. 2010). Shrublands and small trees are the main source of feed for the small domestic mammals of Southern Europe (goats and sheep) during most of the year and especially on summertime. The introduction of deep-rooted perennials in agricultural systems is one of the recommendations of the European Commission EU as part of the indicative measures that may be included in the information on LULUCF actions submitted under Article 10(2)(d) (Decision 529/2013/EU) that can be related to agroforestry. The highest proportion of permanent grasslands in the South of Europe is associated with the better adaptation of grasses than arable crops to the Mediterranean lack of water (Pardini et al. 2010).

1.6. Conclusion

Silvopasture is an important practice across the Mediterranean region, mostly associated with oaklands, but also present in permanent crops (olive) in some areas. The extent of silvopasture is high in the west part of the Iberian peninsula where the share of public land is low as financial benefits are obtained from the land. However, most of the regions have a low extent of silvopasture and can be linked to a high (intensive agriculture) and low (abandonment) anthropogenic pressure. Most of the silvopasture measures related with silvopasture are adapted to the local necessity, mainly associated to regeneration and maintenance in the managed dehesas but linked to forest fire prevention through silvopasture promotion in the majority of the Mediterranean regions of Europe.

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Chapter 3. Climate change and silvopasture: the potential of the tree and weather to modify soil carbon balance

1.1. Abstract

In silvopastoral systems, trees play an important role n the variation of the soil properties the climate change mitigation, mainly due its effect on the soil chemical properties which can be also modified by management practices such as the liming and the organic and inorganic fertilisation. The European Commission promotes the use of sewage sludge as organic fertiliser under its Circular Economy Package to recycle organic matter and nutrients. This study evaluates the soil chemical (pH) and biological (organic carbon) properties, the tree growth (dominant height and tree canopy) and the relationships between the variation of the soil chemical and biological properties and the tree growth during the period 1998-2012 in a silvopastoral system established on an acidic forest soil under Pinus radiata D. Don in Galicia (NW Spain). This silvopastoral system was subjected fourteen years ago to nine fertilisation treatments: three different doses of sewage sludge (160, 320 and 480 kg total N ha-1) or no fertilisation, all with or without liming, and mineral fertiliser (8% N-24% P2O5-16% K2O) with no liming. The results of this experiment showed that the soil pH decreased over time probably due to the cations extraction from the soil by trees and the deposit of acidifying materials such as pine needles linked to mineralization and high precipitation. The proportion of soil organic carbon on soil was carbon also reduced over time, presumably linked to the light interception by trees, which negatively affected the mineralization and incorporation of organic carbon to the soil. Moreover, the fertilisation with sewage sludge, mainly the high doses, increased the soil pH and the amount of soil organic carbon, which did not compensate for the cations extraction from the soil by the trees, mainly in the years after the application of sewage sludge to the soil. Therefore, it seems advisable to apply additional amendments with

higher pH than the soil (lime, sewage sludge) should be applied in the middle to final years of the study to maintain adequate ranges of soil pH and soil organic carbon compensate the cation extractions by trees. Moreover, trees should be pruned, cleared, or thinned to decrease the trees competitiveness and enhance tree growth and enhance carbon incorporation into the soil at the same time that climate change mitigation may be increased. Moreover, control plots should be linked to the eco-schemes of the next Common Agricultural Policy (CAP) 2021-2027 to account for the soil organic carbon levels for future policies.

1.2. Introduction

Agroforestry is defined as the deliberate integration of woody vegetation with a lower story agricultural production (Mosquera-Losada et al., 2018; Santiago-Freijanes et al., 2018). Agroforestry, and therefore silvopasture, is intended to be one of the most useful tools to achieve the upgrading of the rural areas throughout economic, environmental, and social improvements (Cork 2.0 Declaration, 2016). Several studies have shown that agroforestry improves the use of the existing resources (ecointensification) which increases the biomass production and, as a consequence, the amount of soil organic matter (OM), being OM the largest carbon (C) reservoir (81%) in the terrestrial ecosystems (Karsenty et al., 2003; Mosquera-Losada et al., 2018). For this reason, agroforestry has been recognized as a tool for mitigating climate change (Mosquera-Losada et al., 2018) by the "4 per 1000" initiative (Four per thousand, 2019) but also by several international organizations as United Nations (UN) in the Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) (FAO, 2013). Therefore, agroforestry is expanding across Europe despite the lack of technical knowledge transfer and adequate policies promoting agroforestry practices at field level (Mosquera-Losada et al., 2018).

P. radiata D. Don is the most used conifer in afforestation in Galicia (NW Spain), covering an area of around 96.177 ha according to the data offered by the IV National Forest Inventory (2011). In 2016, this conifer represented 15.20% of the Spanish total forest logging, being one of the most important productive species in this country (MAPA, 2019). Moreover, P. radiata has been widely used as tree species in the establishment of silvopastoral systems in Galicia as well as in other regions of Europe (Knowles, 1991; Mosquera-Losada et al., 2011a) and the world (Peri et al., 2007; Dube et al., 2016). In this type of agroforestry systems, P. radiata favours C sequestration due to its high growth rate compared with other conifer and broadleaved species (Fernández-Núñez et al., 2010; Mosquera-Losada et al., 2012; Ferreiro-Domínguez et al., 2014). However, the soil C sequestration ratio and other soil properties such as the soil pH depends on multiple factors such as weather conditions, chemical and physical soil properties or tree and soil management (Lal, 2004). The influence of tree management on soil carbon sequestration has recently gained importance due to an increasing concern on climate change (IPCC, 2019). Several studies have shown that tree management plays a clearly an outstanding role in the tree-understory-soil interaction that affects soil properties such as pH or OM and therefore soil C sequestration (Ruiz-Navarro et al., 2009; Schrijver et al., 2012; Ferreiro-Domínguez et al. 2014). However, experiments like this study with more than 10 years of experimentation in the field are scarce and necessary to evaluate at medium and long term the tree-understory-soil interaction and its influence on climate change mitigation.

Galician soils tend usually to be acidic, limiting both pasture production and tree growth (Zas and Alonso, 2002). High acidic soils are associated with a number of several toxicities such as those derived from aluminium, deficiencies (calcium), and other plant restricting conditions (FAO, 2017). In Galicia, liming and mineral fertilisation are the main practices to increase agricultural production. Sewage sludge (SS) could be used as organic fertiliser due to its high OM and macronutrients and micronutrients content (Environment Agency - U.K. Gov., 2018). Moreover, recent studies have shown that the partial or total substitution of mineral fertilisers by organic fertilisers as SS could be a viable alternative to adopt the Circular Economy Package of the European Commission in the farms (Mosquera-Losada et al., 2019). When SS is used as fertiliser, N should be considered the main indicator to set the different doses of SS to be applied into the soil (Mosquera-Losada et al., 2016). However, it is also important to take into account that heavy metals concentration in the SS is usually higher than in the soil (Smith, 1996). In Europe, the Directive 86/278/CEE (EU, 1986) and in Spain the Royal Decree 1310/1990 (BOE, 1990) regulate the use of SS as fertiliser to diminish the inherent risk of heavy metals toxicity to the soil, plants, and humans.

The objectives of this study were: i) to evaluate changes in soil chemical (pH) and biological (organic carbon) properties (pH and OM), ii) to quantify the tree growth (dominant height and tree canopy) and iii) to establish relationships between the variation of soil chemical and biological properties and the tree growth during the period 1998-2012 in a silvopastoral system established on an acidic forest soil under P. radiata fertilized with SS 14 years ago. This study hypothesizes that the organic and inorganic fertilisation in silvopastoral systems can modify the tree growth and therefore the soil chemical and biological properties such as the pH or the organic carbon at the medium and long term.

1.3. Materials and methods

Characteristics of the study site

The experiment was carried out in Pol (Lugo, Galicia, north-western Spain, European Atlantic Biogeographic Region), at an altitude of 530 m above sea level. Galicia is a transition zone between the Atlantic and Mediterranean climates with mild winters and warm summers. This region is characterised by the high rainfall levels, with well over 1000 mm a year across almost the entire region, and the dry summer months, often resulting in moderate drought conditions.

Figure 1 shows the ombrothermic diagrams with the mean monthly temperatures and precipitation for the 1998-2002 and 2006-2012 periods in comparison with the mean values over the last 30 years. The data of November and December 2002 were not available for the mean monthly temperatures and precipitation due to technical issues at the weather station. In 1999 (1233.3 mm), 2000 (1340.7 mm), 2008 (1222.3 mm), 2009 (1208.6 mm) and 2010 (1303.9 mm) the annual precipitation was higher than the mean precipitation over the last 30 years (1071.5 mm). However, years 2007 (734.4 mm), 2011 (903.3 mm) and 2012 (781.8 mm) had lower annual precipitation than the annual 30 years mean for the study area. The annual mean temperatures during the studied period were warmer compared with the mean temperature over the last 30 years (11.6 °C), especially in 2006 (12.8 °C) and 2011 (13 °C) when the mean annual temperature raised up to more than 1ºC in comparison with the historical data, probably as a consequence of climate change. The mean daily temperatures of the coldest (November, December, January and February) and the warmest (June, July, August and September) months during the studied period are 7.1 °C and 17.6 °C respectively. Given the above and according to the dry season index (Precipitation<2*Temperature) (Gaussen and Bagnouls, 1953), drought periods were observed in almost all years during the summer (July, August and September). Some particularities were observed in 1998 (two drought periods in June and August), 2000, 2001 and 2005 (earlier drought in May and June) but also in 2011 when it was found a lack of precipitation in winter and an early drought in June.

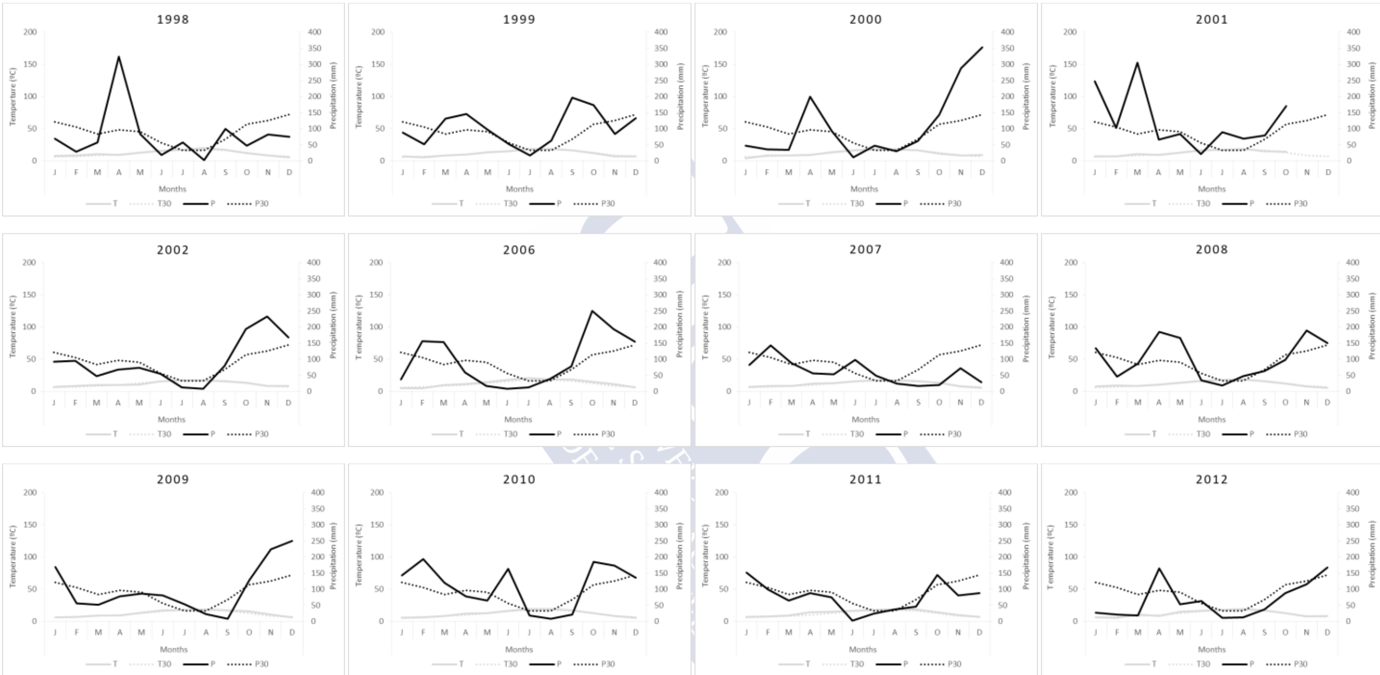

Figure 1. Monthly precipitation and mean temperatures for the study area from 1998 to 2012 and mean data for the last 30 years. T: mean monthly temperature (˚C), T30: mean temperature over the last 30 years (˚C), P: monthly precipitation (mm), and P30: mean precipitation over the last 30 years (mm).T: mean monthly temperature (ºC), P:

The experiment was carried out on an afforested land settled on quartzite as parent rock material, with a loam-clay-sandy texture (62.9% sand, 26.4% clay, and 10.7% silt), classified as Umbrisol (FAO, 1998) and whose depth is above 50 cm. Before establishing the study, the soil was very acid (soil pH of 4.97) with an OM concentration of 12.3%. The total N concentration was high (0.52%) but the total concentration of P (0.03%) was low as well as the concentrations of K, Ca, Mg and Na extracted with $BaCl_2$ (cmol(+) kg^{-1}) (K: 0.13; Ca: 1.35; Mg: 0.41; Na: 0.49) indicating a low Cation Exchange Capacity and a high Al saturation percentage (55.13%), which usually implies toxicity for plants. Moreover, the heavy metals concentrations in the soil were low and far below the limit allowed by law regarding the application of SS as fertiliser in the agriculture set by the European Union Directive 86/278/CEE (EU, 1986) and Spanish R.D. regarding soils with pH lower than 7 (BOE, 1990; Mosquera-Losada et al., 2012).

Experimental design

The study was established in a five-year-old P. radiata plantation in 1997. The initial tree density was 1667 trees ha^{-1} and the mean height and diameter of the trees were 2.15 m and 5.19 cm, respectively, (height standard error was 0.12 m and diameter standard error was 0.29 cm). In October 1997, the existing scrub in the understory was cleared with a rotary brush cutter and later the soil was ploughed before plots establishment. Twenty-seven plots were established with an area of 96 m^2 each, delimited by plantation lines, including each plot a total of 25 trees arranged in a 5 x 5 trees square. In autumn 1997, the plots were fertilised with 120 kg P_2O_5 ha^{-1} and 200 kg K_2O ha^{-1} and sown with a mixture of 25 kg ha^{-1} of Lolium perenne L. cv "Brigantia", 10 kg ha^{-1} of Dactylis glomerata L. cv "Artabro" and 4 kg ha^{-1} of Trifolium repens L. cv "Huia". The experiment was settled as a randomised block design with three replicates and nine treatments. The nine tested treatments were a no fertilisation (NF) treatment and three SS doses based on its N addition to soil (S1: 160 kg total N ha^{-1}; S2: 320 kg total N ha^{-1}; and S3: 480 kg total N ha^{-1}) with or without liming (2.5 t

$CaCO_3$ ha^{-1}). In the no-limed plots, a control mineral treatment (MIN) was also included in which 500 kg of 8% N – 24% P_2O_5 – 16% K_2O ha^{-1} complex fertilizer was applied from 1998 to 2006 in accordance with the traditional fertilisation usually carried out in the Galician grasslands. The mineral treatment was not included in the limed plots because the combination of lime with mineral fertiliser is not a conventional practice in the area. Sewage sludge was applied by hand in March 1998, 1999, and 2000. Moreover, in order to evaluate the residual effect of the SS and to incorporate some sludge patches found in the plots fertilised with SS (mainly in high doses) into the soils, mineral fertiliser was applied in the plots previously fertilised with SS from 2001 to 2006.

Sewage sludge

The anaerobically digested SS came from the wastewater treatment plant managed by the company Gestagua S.A. in the city of Lugo (NW Spain) (Mosquera-Losada et al., 2012). The SS doses were based on the percentage of total N and dry matter of the SS, following the recommendations of the U.S. Environmental Protection Agency (EPA) (EPA, 1994). In addition, the concentration of heavy metals in the SS was far below the legal maximum limit regarding SS addition to soils with a pH under 7 as it is indicated in the R.D. 1310/1990 (BOE, 1990).

Field samplings and laboratory analyses

During the periods 1998-2002 and 2006-2012 composite soil samples were collected each year in each plot in December at a soil depth of 25 cm as required in the R.D. 1310/1990 (BOE, 1990). Soil samples were air-dried and sieved at 2 mm and ground with an agate mortar. The pH determination was carried out in water with a 1:2.5 ratio (Faithfull, 2002; Guitián and Carballas, 1976). In 1998, 1999, 2000, 2006, 2007, 2008, and 2009 the total soil organic carbon content in the soil (SOC) was estimated by oxidation of the total OM with potassium dicromate and sulphuric acid. The excess of dicromate was valorated with Mohr salt (Kowalenko, 2001). However, in 2001, 2002, 2010, 2011, and 2012 the total SOC content in the soil was determined with a LECO CNS-2000 analyzer (LECO, 1996). In both cases the percentage of OM was calculated by multiplying the total C content of the soil by the de Van Bemmelen factor (1.724).

The total height of the nine central trees of each plot was measured in 1998, 1999, 2000, 2004, 2006, 2007, 2009, 2011, and 2012. The dominant height was calculated as the average height of 20% of the thickest trees in the plot (Weise, 1880). Tree height was measured with a telescopic pole when trees were below 8 m and with a Vertex when trees exceeded it. Moreover, the crown diameter of the nine central trees of each plot was also measured in the years 1998, 2004, and 2006 in order to determine the percentage of tree canopy cover. A tape measure and a vertex were used for measuring these variables. Finally, it is important to be aware that pruning labours were carried out in 2002 in order to improve wood quality.

The percentage of pine needles in the understory regarding the total biomass was determined by randomly collecting two biomass samples in each plot. The samples were cut with an electric hand clipper at a height of 2.5 cm (0.3 m × 0.3 m) in July during the periods 1998-2002 and 2006-2012. At the laboratory, samples were separated by hand according to the different species, senescent material, and pine needles and then dried (72 h at 60 ◦C) to determine their composition on a dry weight basis. Pine needles accumulated in the understory were removed from the soil after biomass sampling every year.

Statistical analysis

The data were analysed with repeated ANOVA measures (proc glm procedure), and Mauchly’s criterion was used to test for sphericity. If the sphericity assumption was met, then the univariate approach output was used. Otherwise, multivariate output (taking into account Wilks’ Lambda test) was used. The statistical model used was $Y_{ij}=\mu+A_i+T_j+TA_{ji}+\varepsilon_{ij}$, being Y_{ij} the variable, μ the mean of the variable, Ai the year i, Tj the treatment j, TAji the interaction treatment-year and εij the error.

The results obtained in soil and trees in each year were also treated by using an ANOVA (proc glm) but with this other statistical model $Yik=\mu+Ti+Bk+TBik+ \varepsilon ik$, being Yik the variable, μ the mean of the variable, Ti the treatment i, Bk the block k, TBik the interaction treatment-block and εik the error.

The least-significant difference (LSD) test was used for subsequent pairwise comparisons ($p<0.05$; a = 0.05) if the ANOVA was significant. The statistical software package SAS (2001) was used for these analyses.

Linear regressions were calculated and performed employing Excel Software on the previously processed data, by creating a combination chart and adding a trend line to it.

1.4. Results

Ombrothermic diagrams

Figure 1 shows the ombrothermic diagrams with the mean monthly temperatures and precipitation for the 1998-2002 and 2006-2012 periods in comparison with the mean values over the last 30 years. The data of November and December 2001 were not available for the mean monthly temperatures and precipitation due to technical issues at the weather station. In 1999 (1233.3 mm), 2000 (1340.7 mm), 2008 (1222.3 mm), 2009 (1208.6 mm) and 2010 (1303.9 mm) the annual precipitation was higher than the mean precipitation over the last 30 years (1071.5 mm). However, 2007 (734.4 mm), 2011 (903.3 mm) and 2012 (781.8 mm) had lower annual precipitation than the annual 30 years mean for the study area. The annual mean temperatures during the studied period were warmer compared with the mean temperature over the last 30 years (11.6 °C), especially in 2006 (12.8 °C) and 2011 (13 °C) when the mean annual temperature raised to more than 1ºC in comparison with the historical data, probably as a consequence of climate change which can modify the soil chemical and biological properties. The mean daily temperatures of the coldest (November, December, January, and February) and the warmest (June, July, August, and September) months during the studied period were 7.1 °C and 17.6 °C, respectively.

Finally, according to the dry season index (Precipitation<2*Temperature) (Gaussen and Bagnouls, 1953), drought periods were observed in almost all years during the summer (July, August, and September). Some particularities were observed in 1998 (two drought periods in June and August), 2000, 2001 and 2005 (earlier drought in May and June) but also in 2011 when it was found a lack of precipitation in winter and an early drought in June

Soil

Soil pH

Figure 2 shows that the soil pH was generally reduced from the beginning to the end of the experiment ($p<0.001$). Higher values of soil pH were found in 1998 and 2002 while the lower ones appeared in 2006 and 2010. Moreover, soil pH was modified by treatments from the beginning (years 1999 ($p<0.01$), 2000 ($p<0.001$), 2001 ($p<0.05$), and 2009 ($p<0.05$)) until the end of the experiment (Figure 3). In 2000, liming increased soil pH when the lime was combined with different doses of SS (S1, S2, and S3). The positive effect of the lime on the soil pH was also observed in 2001 in the plots fertilised with low doses of SS (S1). However, in 1999 and 2009 the soil pH was not significantly modified by the application of lime to the soil, initially probably associated to with the lack of time to show the effect and at the end, because of the reduction of the lime effect at the medium and long term. Regarding SS addition to the soil in limed plots, soil pH was higher in S2 and S3 compared to the NF treatment in 2000. On the contrary, soil pH increased with S1 in comparison with the S2 and S3 doses in 2001 when lime was applied. In 2009, in no limed plots, soil pH was also higher when S1 dose was applied compared to S2 and NF treatment.

Finally, MIN presented a lower soil pH value than other treatments, with the exception of the no-limed treatments NF in 1999, NF and S1 in 2000, NF and S3 in 2001 and NF and S2 in 2009.

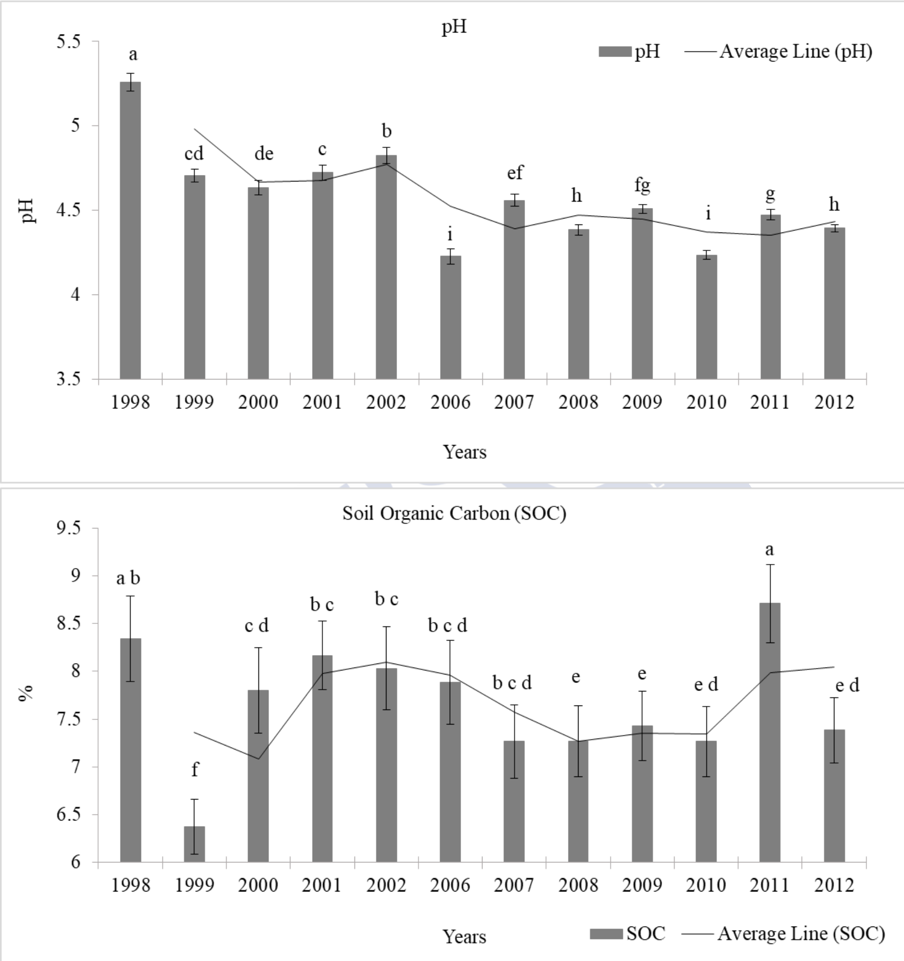

Figure 2. Soil pH and levels of soil organic carbon (SOC) (%) through the studied period (1998-2012). Different letters indicate significant differences between the years. Bars in each column indicate the standard error of the mean.

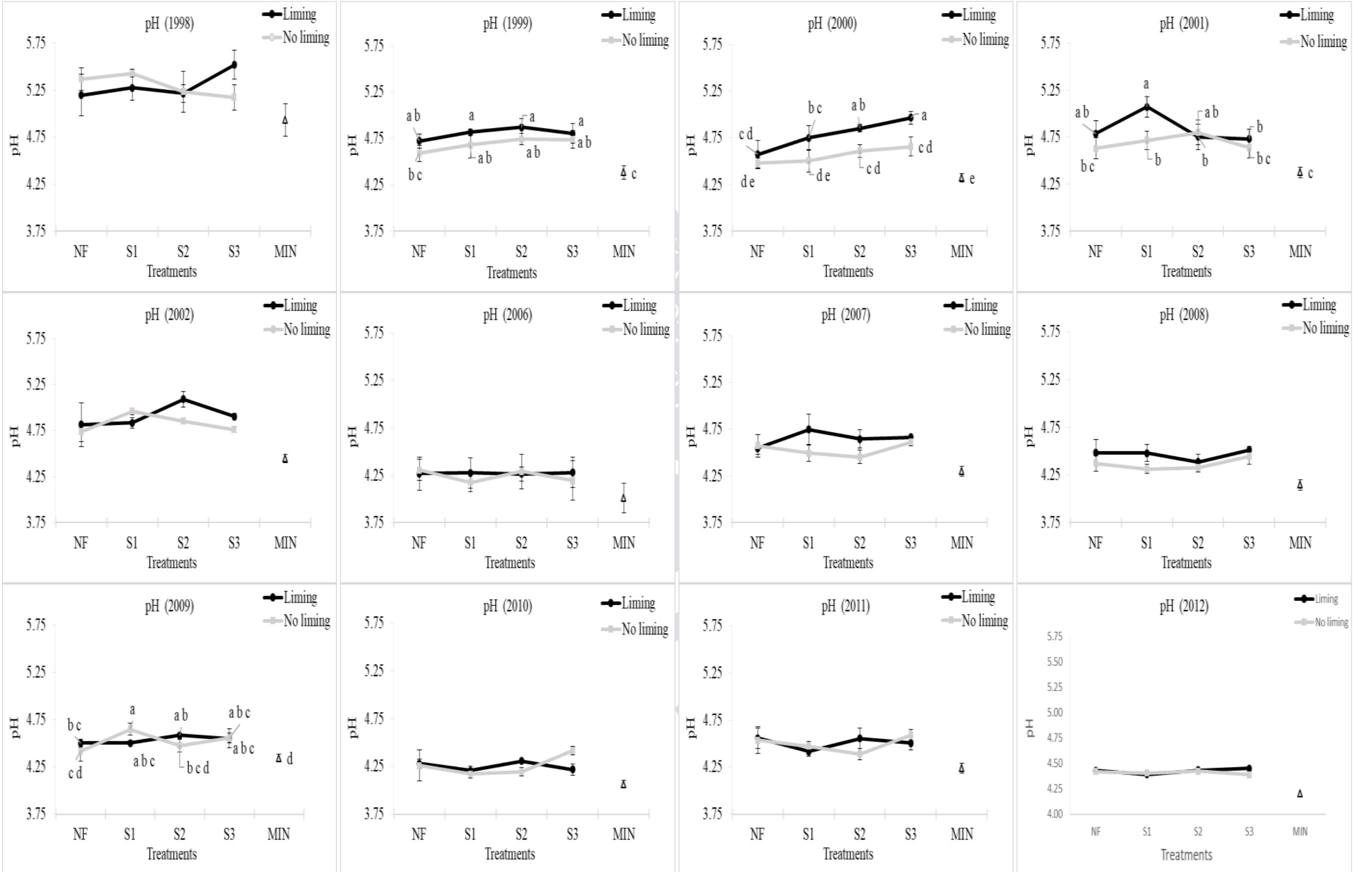

Figure 3. Soil pH under each treatment through the studied period (1998-2012). NF: no fertilisation; S1: low sewage sludge dose (160 kg N ha-1); S2: medium sewage sludge dose (320 kg N ha-1); S3: high sewage sludge dose (480 kg N ha-1); MIN: mineral fertilisation. Different letters indicate significant differences between the fertiliser treatments

Soil Organic Carbon

Soil organic carbon ranged between 6.3710.99-8.7115.02% (Figure 2), being this soil variable significantly modified by the interaction between year and treatment ($p<0.001$). In this experiment, the soil SOC generally decreased from 2006 to the end of the experiment, with the exception of 2011. Figure 4 reflects that lime addition to the soil favoured a decrease in SOC levels in 2009 when the S3 dose was applied. Moreover, in 1999, in the limed plots, the S3 dose increased the soil SOC compared with S1. In the limed plots, it was also observed that the soil SOC was lower in the NF treatment than when S1 and S2 were applied in 2009. A negative effect of the NF treatment on the SOC levels was also observed in the plots without lime compared with S3 in 2006 and 2007 and with S1 in 2008 and 2010. Finally, in the no-limed plots, the MIN treatment decreased more the soil SOC than S3 in 1999 and all fertilisation doses treatments in 2009 (S1, S2, and S3).

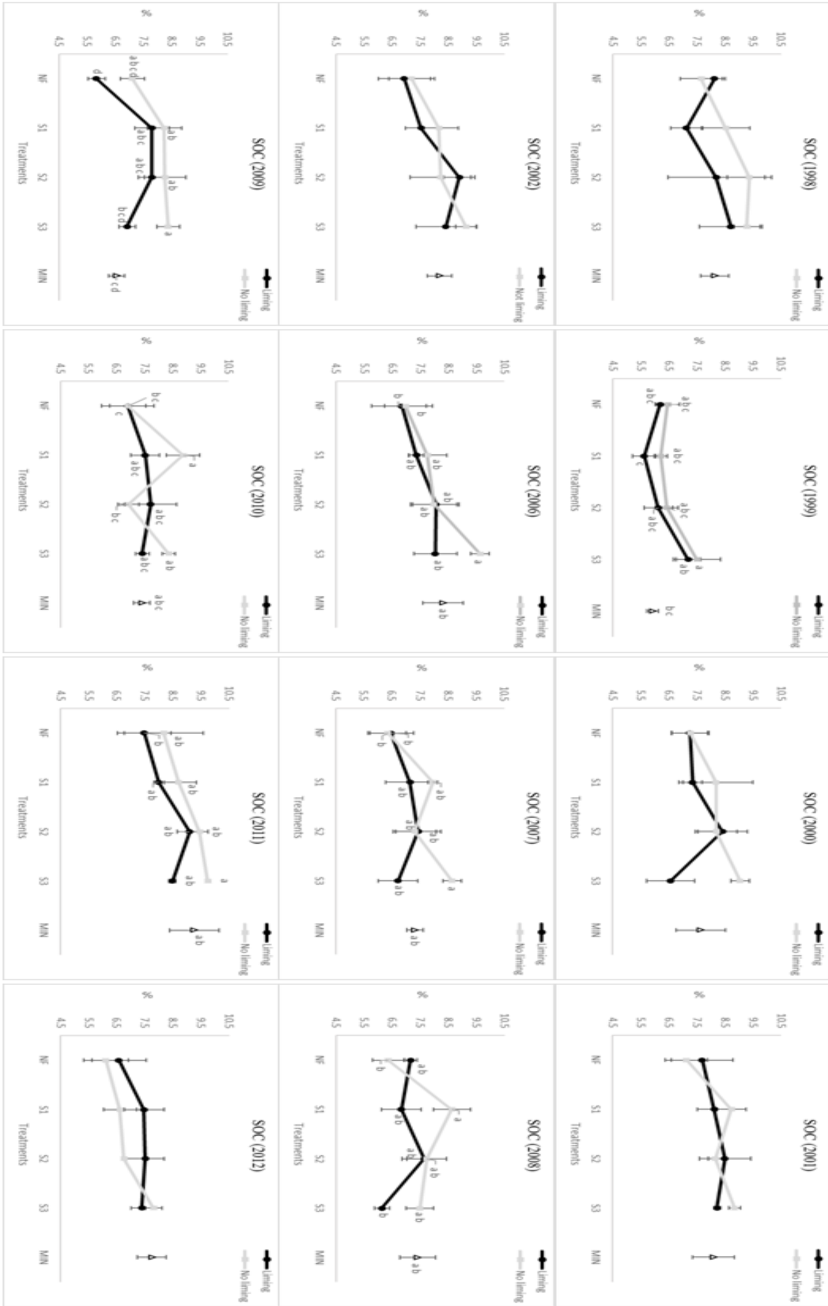

Figure 4. Soil organic carbon (SOC) (%) values under each treatment through the studied period (1998-2012). NF: no fertilisation; S1: low sewage sludge dose (160 kg N ha-1); S2: medium sewage sludge dose (320 kg N ha-1); S3: high sewage sludge dose (480 kg N ha-1); MIN: mineral fertilisation. Different letters indicate significant differences

Tree

Tree dominant height

Tree dominant height grew steadily during all the study period until it finally reached a mean of 18.78 m in (2012) (Figure 5). Tree dominant height was significantly modified by the treatments established in 2000, 2006, 2009, 2011, and 2012 ($p<0.05$). A positive effect of liming on the dominant height of the trees was found under the NF treatment from the beginning to the end of the study (years 2000, 2006, 2009, and 2011). Sewage sludge applications (S1, S2, and S3) combined with liming and no liming increased tree dominant height compared with the NF treatment without lime treatment in 2006, 2009, 2011, and 2012. Similarly, MIN increased the tree dominant height when compared to the treatment that did neither receive lime nor sludge (no limed - NF) in 2000, 2006, 2009, 2011, and 2012 while liming S1 treatment showed a higher tree dominant height than limed - NF treatment just in 2011.

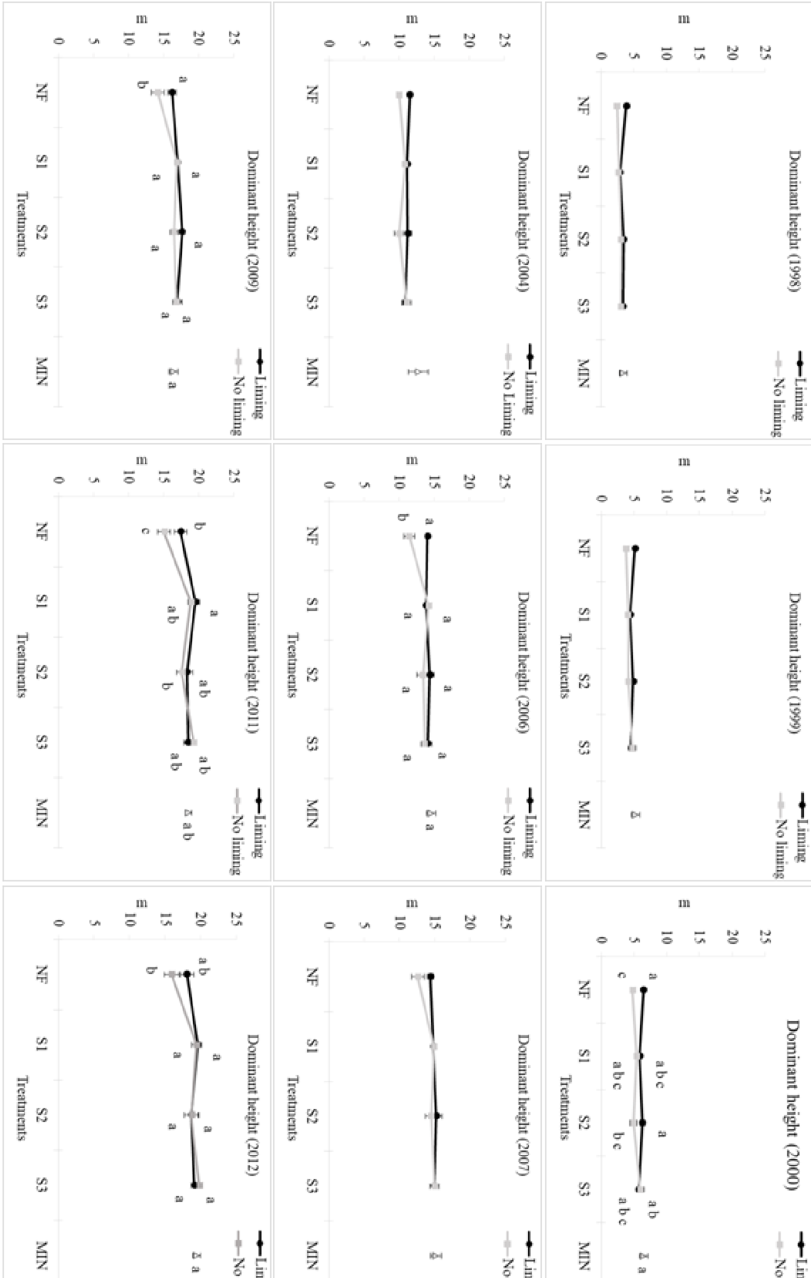

Figure 5. Dominant height values (m) under each treatment through the studied period (1998-2012). NF: no fertilisation; S1: low sewage sludge dose (160 kg N ha-1); S2: medium sewage sludge dose (320 kg N ha-1); S3: high sewage sludge dose (480 kg N ha-1); MIN: mineral fertilisation. Different letters indicate significant differences

Tree canopy cover

Canopy cover was not affected by treatments (Figure 6). Nonetheless, a tendency related to liming favouring canopy cover development when NF or S2 were applied in 1998 and 2004 can be observed. Canopy cover response to the SS and MIN fertilisation was not clear in any of the years of study but both treatments seem to favour a sooner canopy cover closure as observed for S2, S3, and MIN in 2006.

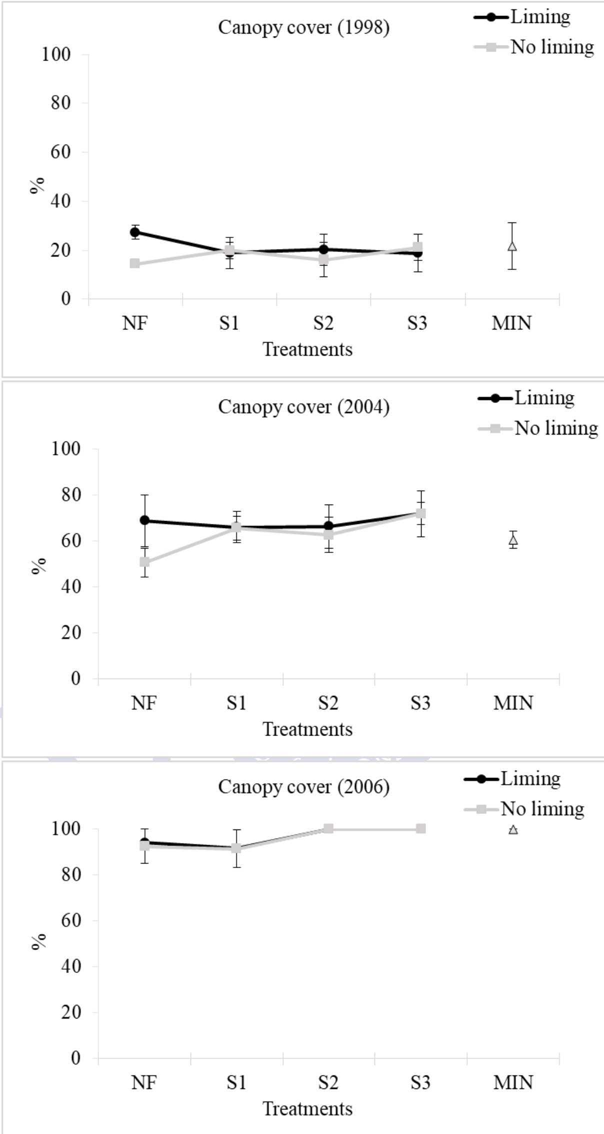

Figure 6: Tree canopy cover (%) under each treatment through the studied period (1998-2012). NF: no fertilisation; S1: low sewage sludge dose (160 kg N ha-1); S2: medium sewage sludge dose (320 kg N ha-1); S3: high sewage sludge dose (480 kg N ha-1); MIN: mineral fertilisation. Different letters indicate significant differences between the fertiliser treatments in each year. Bars indicate the standard error of the mean.

The percentage of pine needles in the understory regarding the total biomass (Figure 7) increased over time, mainly from 2006 ($p<0.001$). However, a lower percentage of pine needles in the understory was observed in 2011 compared with the three previous years and the last year of the study.

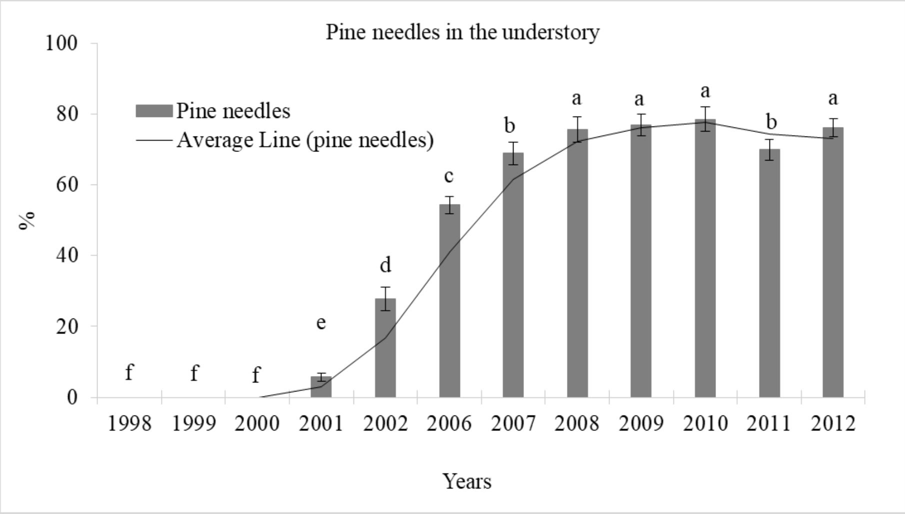

Figure 7. Pine needles in the understory (%) regarding the total biomass through the studied period (1998-2012). Different letters indicate significant differences between the years. Bars in each column indicate the standard error of the mean.

Soil and tree relationship

Significant linear regressions were found pairing tree height – soil pH and tree canopy cover – SOC in order to determine how forest cover affects soil parameters. Regression between tree height and soil pH provided the equation “pH=-0.04*height+5.05” which goodness-of-fit works as an R2=0.62 while Pearson´s correlation showed a value of 0.79 (Figure 8). Therefore, it is observed an inversely proportional relationship between the soil pH and the tree height was observed in which an increase of the tree height implied a reduction of soil pH.

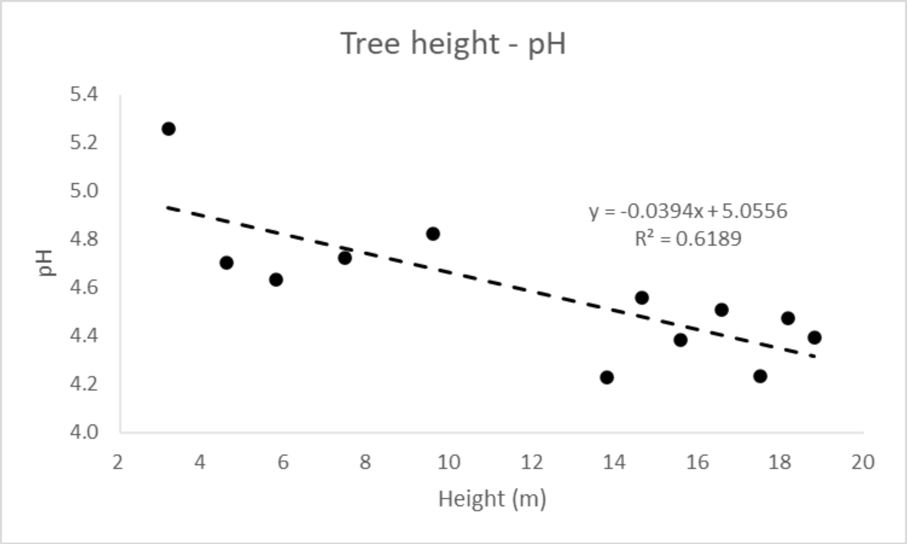

Figure 8. Relation and linear regression between tree height (m) and soil pH during the studied period (1998-2012).

Paired tree canopy cover and soil SOC regression spawned the equation "SOC=-0.02*Canopy Cover+14.53" with an R2 coefficient of determination value of 0.73 and Pearson´s coefficient up to 0.85 (Figure 98). Tree canopy cover highest values seem to affect negatively SOC values in the way that more canopy cover is associated with less SOC incorporated to soil.

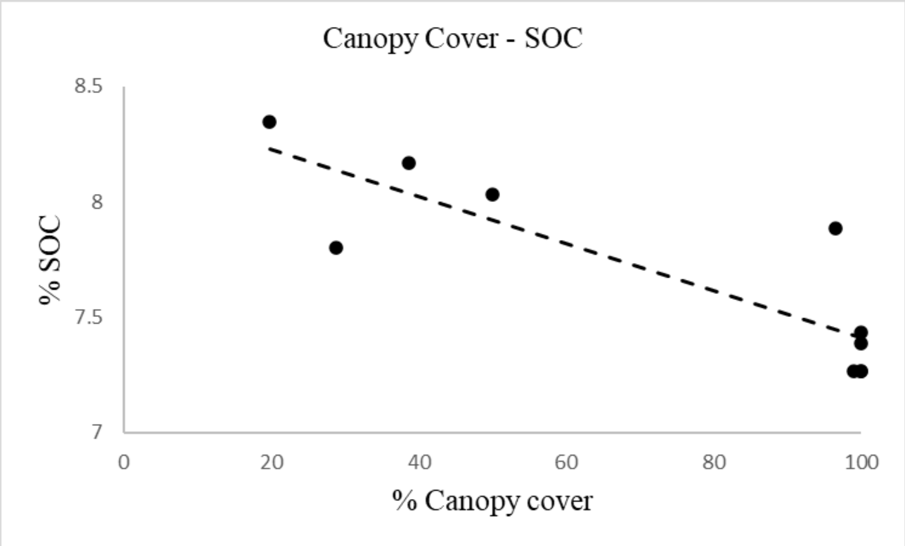

Figure 9. Relation and linear regression between tree canopy cover (%) and soil organic carbon (SOC) (%) during the studied period (1998-2012).

1.5. Discussion

Tree dominant height observed in the last year of this experiment (15.95-19.82) was within the range established by Sánchez-Rodríguez et al. (2003) in Galicia for an age of 20 years in the II (15-19 m) and III (19-23 m) site-quality classes. Moreover, the tree dominant height obtained in this experiment was higher than those found in other silvopastoral systems established also in Galicia under P. radiata but fertilised with lower SS doses (50 and 100 kg total N ha-1) compared with the doses applied in this study (Mosquera-Losada et al., 2011a). Regarding the effect of the established treatments on the tree dominant height, in this study, the tree height was generally higher when the lime and organic or inorganic fertilisers, were applied into the soil compared with the no fertilisation treatment, independently of the SS doses. Similar results were previously described by numerous authors who described that management practices such as liming and organic and inorganic fertilisation enhance the chemical and physical soil properties and therefore the tree growth (Ferreiro-Domínguez et al., 2014; Mosquera-Losada et al., 2012; Saarsalmi et al., 2011). Despite the positive effect of the liming and organic and inorganic fertilisation on the tree height found by several authors, these management practices are not generally linked to tree management probably because it is costly. However, it seems that tree growth could benefit from liming and fertilisation, as shown in our study. In the case of the canopy cover, no significant effect of the treatments was found on this tree variable probably because the canopy closure occurred early, being this factor similar to all types of treatments due to the previous competition among trees.

In this study, a clear influence of the tree growth and the subsequent canopy closure on the variation of the soil pH and the SOC over time was observed. Regarding the soil pH, the top values of soil pH barely up to 5.3, which indicate that this experiment was established in a very acidic soil (Andrades and Martinez, 2014). The soil acidity could be mainly explained by the parent rock material generating sandy soils, the acidification usually caused by conifers, and the Galician rainfall regime which is characterised by high precipitation rates during most of the year (Álvarez et al., 2002). The adequate profile of precipitation and temperature reduces soil pH because it favours cations extraction. On one hand, these climate conditions increase biomass that uptakes more nutrients from the soil and on the other hand because it facilitates the cations leach through the soil profile and contributes essentially to the natural acidic trend of the soils in this region (Álvarez et al., 2009; Macías et al., 1978). In this experiment, the significant correlation found between soil pH and tree dominant height allows us to assume that the uptake of soil cations by trees was the predominant process over lime and SS addition that decreased the soil pH over time. The negative effect of fast-growing conifer plantations on soil pH was previously observed in afforested areas with Pinus nigra Arnold (Adams et al., 2001) and in silvopastoral systems also established under P. radiata

(Giddens et al., 1997; Mosquera-Losada et al., 2006). Moreover, in this study, both the liming and the fertilisation with SS probably improved This is due to the positive effect of fertilisation with SS on the N mineralisation due to the reduction of the C/N relationship (Whitehead, 1995Mosquera-Losada et al., 2016) which made more significant relevant the uptake of cations by the trees and the understory vegetation than the beneficial effect of liming and SS on the soil pH (Mosquera-Losada et al., 2006). Moreover, it should be noted that the beneficial effect of lime on the soil pH decreased in the medium and long term. However, the beneficial effect of the SS on soil pH was maintained throughout the study (Mosquera-Losada et al., 2012), mainly when the high doses of SS (S3) were applied in comparison with the mineral and the no fertilisation treatments. The positive effect of the fertilisation with SS on soil pH could be explained by the Ca input into the soil (Tsadilas et al., 1995). Thereby, although the low SS doses (S1) implied a lower total input of Ca (S1: 230 kg CO3Ca ha−1) into the soil than the other doses (S2: 461.4 kg CO3Ca ha−1 and S3: 692.4 kg CO3Ca ha−1), S1 increased more the soil pH than S2 and S3 in 2001 and S2 in 2009. The negative effect of S2 and S3 on soil pH compared with S1 could be due to the difficulty of incorporation of the high doses of SS into the soil but also due to the higher pasture production obtained when the soil was fertilised with medium and high doses of SS compared with the low doses in which the soil conditions remained very poor, as happened in 2001 (Mosquera-Losada et al., 2012). The higher soil pH and lower pasture production associated to S1 at the beginning of the study (Mosquera-Losada et al., 2012) probably had an early positive effect on tree dominant height which was maintained until the end of the study because in 2011 the tree dominant height remained generally higher in S1 compared with the other treatments. Moreover, the MIN fertilisation applied in all the experimental plots from 2001 to 2006 could have also increased cations extraction from the soil by the understory vegetation but mainly by tree roots due to their potential to explore a large soil volume and deeper soil layers in comparison with the understory vegetation roots (Alburquerque et al., 2013; Ferreiro-

Domínguez et al., 2016). Therefore, in this experiment, it seems that to maintain an adequate range of soil pH the application of additional amendments with higher pH than the soil (lime, SS) is advisable in the middle years of the tree plantation which may compensate the extractions of the different cations by the trees. Finally, the soil pH could have also been reduced at the end of the experiment due to the deposit of acidifying materials from the trees such as pine needles, mainly from 2006 when tree canopy reached the closure (Fisher and Binkley, 2012). In this context, it is also important to be aware of the allelopathic effect of pine needles on understory vegetation. Most of the studies on allelopathy in gymnosperms have been attributed to the leachable extracts (predominantly phenolics) of needles that have fallen to the soil (Singh et al., 1999; Cimmino et al., 2014). These extracts from needles can inhibit herbaceous plants that grow under pine trees, explaining why little vegetation is seen growing under pine trees (Teixeira da Silva et al., 2015).

In the case of the SOC, the values found in this experiment were similar to those described in previous studies developed in the same area (>12.08%) in which more than seven thousand soil samples were analysed under different land uses in the area (Anta et al., 2015). The high SOC characterizing Galician soils are mainly due to the enormous inputs of OM organic matter from the vegetation associated with warm temperatures and adequate water availability along throughout the year, which makes Galicia the region of Europe with the highest forest growth rates. The high organic matter inputs together with the low soil pH limiting the soil mineralization mechanism causes a higher soil organic matter compared with other Spanish soils where weather limits the biomass incorporation as the main carbon source in terrestrial ecosystems and the high pH favours the incorporation and mineralization of the OMSOC in the soil (Howlett et al., 2011). As in the case of the soil pH, in this experiment, the variation of the SOC over time depended on the tree age and the subsequent canopy closure, as it happened to but also of the weather conditions. At the beginning of the study, when the influence of the tree canopy was low, a clear negative effect of liming and fertilisation with SS on the levels of SOC was observed.. Thus iIn 1999, the liming and the application of SS probably decreased the SOC compared with 1998 because these management practices generally increase the mineralization rate of the soil OM (Flower and Crabtree, 2011; Melvin et al., 2013; Paradelo et al., 2015) (Paradelo et al., 2015). Moreover, the larger annual rainfalls registered in 1999 (1233 mm) compared with the mean of the last 30 years (1071.5 mm) probably also increased the mineralization rate of the soil OM because the soil moisture is a key factor in the OM mineralisation (EPA, 1994Mosquera-Losada et al., 2011b). From 1999 to 2006, the SOC increased which could be due to the addition of OM to the soil with the SS (Dai et al., 2017) and the pasture establishment as a major soil OM source from roots and senescent material (Mosquera-Losada et al., 2011b) but also due to the application of SS to the soil (Dai et al., 2017), mainly the high doses (S3). The (Mosquera-Losada et al., 2011b).application of SS to the soil probably implied higher inputs of OM (needles) into the soil compared with the no fertilisation treatment as trees growth was better in the SS treatments (Mosquera-Losada et al., 2012). The increase of the SOC levels and soil pH associated with the fertilisation with SS compared with NF treatment indicates that this type of waste could be an important source of nutrients, contributing to the bioeconomy (EC, 2018) and circular economy (EC, 2020) concepts of the European Commission. However, from 2006, when tree canopy reached the closure (>96%), the SOC generally decreased to the end of the experiment in spite ofdespite the pine needles fall down. This result could be explained because the conditions of temperature, humidity, and aeration in the understory probably were negatively affected by the tree canopy growth which reduced the soil biota activity and therefore the incorporation of the fallen pine needles into the soil (Pérez-Batallón et al., 2001). Moreover, from 2006 the needles of the canopy lower-stratus increased fall once the canopy cover reached the closure. The pasture of the understory vegetation was replaced by the fallen pine needles into the soil which were accumulated in soil surface without being incorporated into the soil because pine needles break down at a slow rate compared with the leaves of broadleaves species (Rigueiro-Rodríguez et al., 2012). The significant correlation found in this study between SOC and tree canopy cover indicates us that the tree canopy cover development influenced SOC OM by modifying crucial processes such as the incorporation and mineralization of the needles (OM) soil inputs (Gallardo, 2003; Rousk et al., 2009). Therefore, in this study, it seems to be highly advisable to carry out management activities on the plantation (pruning, clearing or thinning) to improve soil biota activity and to increase the incorporation of the OM into the soil which could favour the recycling of nutrients in the system as well as the soil C sequestration (Nair et al., 2010). These recommendations are in line with the IPCC (2019) to enhance mitigation efforts against climate change. Finally, it is also important to be aware that in 2011 an atypical top SOC value was found compared with the previous years. This result could be due to an unusual warm temperatures in 2011 (13 °C) compared with the mean temperature over the last 30 years (11.6 °C), which probably fostered pine needles litter incorporation into the soil in that year, by triggering its decomposition by soil microorganisms (Burés, 1997). In other experiments established in Galicia, it was also observed that SOC depended among other factors on the mean temperature of the months before soil sampling (Mosquera-Losada et al., 2011b). Therefore, in rainy regions like those in this experiment, small variations of the mean temperature can explain the high interannual variation of SOC as it causes a significant effect on soil microbiota and therefore on the processes they cause. In this context, the next Common Agricultural Policy (CAP) 2021-2027 will include the eco-schemes which are mandatory schemes for Member States and voluntary for farmers to maximise environmental and climate benefits such as the SOC sequestration with direct payments from Pillar 1 of the CAP (Meredith and Hart, 2019). In this study, it was found that the levels of SOC depended of the weather conditions of a given year. For this reason, control plots should be established to check if the plots managed by the farmers increase the SOC compared with the unmanaged plots, regardless of the weather conditions. Eco-schemes offer a new possibility to care for the environment and climate, thus supporting the transition towards more sustainable farming systems and contributing to the net-zero emissions in the agriculture sector in 2050 (Lóránt and Allen, 2019).

1.6. Conclusion

Tree growth increased cations extraction from soil and modified the understory microclimate which decreased the levels of soil pH and SOC in the soil over time. However, a positive effect of the fertilisation with SS on soil pH and SOC was observed, mainly in the case of the high doses of SS, which did not compensate for the cations extraction from the soil by the trees, mainly in the years after the application of SS into the soil. Therefore, it is seems advisable to apply additional amendments with higher pH than the soil (lime, sewage sludge) in the middle-ending years of the tree plantation to maintain adequate ranges of soil pH and SOC to compensate for the cation extractions by trees. Moreover, plantation management activities such as clearing, pruning or thinning could also be carried out to decrease tree competitiveness and enhance tree growth and carbon incorporation into the soil at the same time as climate change mitigation may be increased. Moreover, control plots should be linked to the eco-schemes of the next Common Agricultural Policy (CAP) 2021-2027 to account for the soil organic carbon levels for future policies.

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Discussion

The Mediterranean climate is characterized by mild humid winters and hot temperatures with lack of precipitation in summer, which might influence the predominance of perennial crops, permanent grasslands or permanent crops (mostly olive groves and in some Spanish areas nut trees and/or vineyards), as the dominant vegetation in this area (EEA 2002). The highlighted predominance of perennial vegetation in most of the Mediterranean regions of Europe turns silvopasture in the traditional dominant type of agroforestry practice that should be and is applied in most of the Mediterranean areas (Papanastasis 2004). On the other hand, silvoarable practices extent in Mediterranean Europe is quite reduced, being mostly associated to those areas where agroforestry systems are the main type of land use such as the “montado” or “dehesa” in Portugal and central-western Spain, respectively. Depending on the type of woody perennials, silvopasture practices influence forestlands (pine stands, oaklands and shrublands) or agricultural lands (low tree density areas or permanent crops as fruit trees). Thus, the type of dominant vegetation determines the type of agroforestry system and its management. Furthermore, the Mediterranean areas with the lowest extent of agroforestry are those with the highest population density, consequence of the increasing population consumption pressures and availability of important infraestructures, but also those with the lowest population density, such as Aragón in Spain, since farmers depletion downgrade its role as agroforestry catalyst in the Mediterranean areas of Europe and therefore the rural depopulation caused a decrease in the number of farmers, being farmers the main actor in agroforestry development (Margaras 2019). The stressed anthropogenic pressure, linked to intense pastoral and arable activities in Mediterranean forest, caused a reduction in pine-oak forests for centuries (Gassner et al. 2020). In the last decades, land abandonment associated to land degradation, water scarcity linked to climate change, rural depopulation and policies supporting reforestation and afforestation at EU and national level (Santiago-Freijanes et al.

2018) have promoted the recovery of forestlands as the dominant vegetation in the majority of the Mediterranean regions. In addition, the presence of woody perennials in most of the Mediterranean area of Europe can also be related to the fact that deep-rooted species are needed to overcome the long and dry summer that Mediterranean plants have to face (Chaves et al. 2002).

The most extended woody perennials in silvoarable practices are olive trees, which are usually intercropped by two main reasons, obtain an extra income and reduce the negative impact of soil erosion associated to those ploughed and bared soils. The necessity to improve soil fertility turns Mediterranean areas in fertilizer-dependants. For this, Europe needs to overcome price volatility and the expected shortage of fertilizers in the continent in the near future, which could be addressed by the use of renewable resources such as compost from woody perennials or biochar in order to enhance soil fertility (EU 2019a/1009) in arable lands. In this light, Castilla and León and Castilla la Mancha regions in Spain, with cereal crops as predominant agricultural land use, promote livestock systems either through fodder crops seed to be grazed or because animals graze crop residues. Grazing crop residues can be associated with mixed farming systems (EIP-Agri 2017) which is key to reduce the inputs on fertilizers in the farm.

On the other hand, in the Mediterranean areas, the dehesa is recognized to be the most important agroforestry system associated with livestock. This model achieves land use sustainability, being a climate change mitigation tool, a hotspot of biodiversity and enhancing resilience considering its low forest fire risk (Mosquera-losada et al., 2009). The dehesa/montado area presents the largest share of silvopasture of the Mediterranean region linked to agricultural land (including permanent crops) and also to forest lands, where grazing is part of the shrublands and woodlands. The profitability and multiple ecosystem services this system provides influence Portugal and Extremadura being the regions with the lowest share of public ownership of oaklands in Europe (Moreno et al. 2018). Also a low oaklands public ownership rate appears in Catalonia and Mediterranean regions of France due to its high population density. Taking into account the high integration of agroforestry in the dehesa systems, the number of policy measures associated with this land use is very high compared to with most of theother land uses in the Mediterranean regions in the Mediterranean part of Europe. Dehesa regeneration in forest and agricultural lands due to the age of the trees (centuries-old) is the most covered topic by policy measures. Besides, the lack of regeneration associated to inadequate grazing management and climate change (Moral et al. 2014; Fernández-Habas et al. 2019; Rolo et al 2012, 2013) and the protection of dehesas/montado in Spain and Portugal makes also important the policy support associated to the agri-environmental measures due to the ecosystem services this system delivers (Howlett et al. 2011).

On the opposite, there are areas where past anthropogenic activity and pressure has severely degraded some Mediterranean areas areas (Perevolotsky and Sheffer 2011 and Vayreda et al 2013). In order to restore these areas, afforestation and reforestation strategies were carried out planting pioneer tree species, such as pine, to protect the soil from erosion. Thus, regions as Murcia, Valencia and Cyprus are currently dominated by pine species being the silvopasture rate of implementation low. Consequentially, the presence of conifer plantations in these areas is usually linked to marginal, degraded and high-altitude areas and very poor soils. Climate change mitigation potential of the conifers linked to the carbon sequestration carbon sequestration potential is generally higher than the agricultural lands one (Zuazo et al. 2014) but its contribution to silvopasture practices falls short when compared to oaklands due to the less shade (animal welfare) and feed resources (acorns) that pines provide (Papanastasis et al. 1995). Furthermore, pine plantations are more prone to drought stress (Gea-Izquierdo et al 2019) and provide fewer ecosystem services (da Silva et al. 2019) than oaklands.

Oaklands extent in the Mediterranean area of Europe is linked to a small number of agroforestry measures while land abandonment eased oakland expansion in most of the European regions boosting the hazard of being fired considering the Mediterranean weather conditions (Perevolotsky and Sheffer 2011 and Vayreda et al 2013). As a consequence, a large number of regions is found to implement silvopasture through the forest policy measure 8.3 associated with forest fire fighting aiming at reducing the understory as fuel. In addition, some regions implement measures associated with forest restoration after forest fires events. Moreover, c

Climate change adaptation also can be conducted in silvoarable systems, being observed in the Mediterranean area during the cereal growth period when compared with the northern European areas. Thus, cereals are harvested at the end of the spring to avoid summer drought and usually sown after the first autumn rains to increase the cereal growth period (Pérez-Camacho et al. 2012). The deep-rooted perennials and the annual cereal fast-growing species can be considered as nature-based climate adaptation mechanisms traditionally existing in this part of Europe where precipitation intra-annual variability is so frequent and that will be exacerbated by climate change (IPCC 2013). Considering this, the introduction of deep-rooted perennials in northern European latitudes to overcome extreme climate events and warming effects of climate change is one of the agroforestry related recommendations of the European Commission EU as part of the indicative measures that may be included in the LULUCF actions submitted under Article 10(2)(d) (Decision 529/2013/EU).

Therefore, aAgroforestry promotion is needed to be conducted for both silvopasture and silvoarable systems as a strategy of mitigation and adaptation to climate change with policies pushing agroforestry practices up in the Mediterranean regions that outstand with a lack of agroforestry practices.

Currently, CAP direct payments to agricultural areas in Europe depend on two predominant types of land use: arable, and permanent crops (orchards) besides permanent grasslands, while Rural Development

Programmes aims at enhancing the production of ecosystem services related with the environment. Thus, in order to bring aims and policy tools together, large cereals and fruit trees areas should be predominantly paid to integrate silvoarable practices. Regarding silvopasture, most of the Italian and French regions have a scarce share of agroforestry practices linked to silvopasture except for Calabria and Basilicata where agroforestry is promoted by the introduction of agroforestry systems as part of the measures 8.2 and 9.5. According to 900 stakeholders participating the EU thematic network Agroforestry Innovation Network Project (AFINET) (AFINET 2018), silvopasture and forest farming promotion in Mediterranean areas should be based on optimized agroforestry management plans based on the local conditions, but also the upgrading of production and resilience and value chains development. Despite the low introduction of silvopasture practices in woodlands and shrublands of the French and Italian regions (compared with other regions of the Mediterranean area of Europe), most of them promote the establishment and maintenance of different forms of silvopasture in forest areas through measures implementation, being those measures also associated to the development of value chains (e.g. Umbria and Sardegna). Shrubland grazing rate highlights in Greece, the country with the largest density of goats of the European countries, probably due to the employ of shrubs as a source of feed (Papachristou 2000). A different approach appears in Aragón, Malta and La Rioja regions, with a land cover dominated by unmanaged shrublands, as the share of silvopasture is low but it is kept higher than Mediterranean areas of Europe not dominated by shrublands. Unmanaged shrublands are transformed into forests (Perevolotsky and Sheffer 2011 and Vayreda et al 2013) while fired forests are usually transformed in open shrublands (Baudena et al. 2019).

On another hand, silvoarable practices are mostly linked to Lucerne and not to the dominant cereal production in the European Mediterranean area. Lucerne is a perennial legume crop with significant root systems and aboveground biomass that contributes to enhance fertility, through organic matter input, and improve soil physical properties consequentially boosting microbial activity, being this useful as such, as part of a rotation, or for the trees (Wezel et al. 2014). Silvoarable practices promotion, introducing trees/shrubs in cereal areas, will help to address climate change related events like heatwaves and sort the expected lack of water out. Thus, trees in a row, hedgerows and isolated trees are key landscape features to promote silvoarable practices in Europe, contributing to buffer climate change effects such as prevalent winds, extreme heats and heavy rains. Moreover, silvoarable practices implementation will boost the provision of ecosystem services (e.g. pollination) while improving soil health by increasing soil organic matter (Torralba et al. 2016) as it is currently promoted by measure 10.1 with a very limited budget. Poplar highlights as an excellent alive tool to introduce in cropland dominated areas in Spain and the rest of Europe (Kachova and Ferezliev, 2020; Paris et al. 2019) considering its adaptability to Mediterranean soils and environmental conditions (Isebrands and Richardson 2014) and fitting as part of the riparian buffer strips. In addition, there is an excellent industry demanding, processing and marketing this type of fast-growing tree species all over the world, including the Mediterranean region with GARNICA in Spain. There is also room within the silvoarable practices for other tree species such as cypresses, being its shape a useful feature to reduce the tree effect of shading on crops. Nevertheless and in contrast with poplar, it is needed to foster adequate cypress based value chains (Papanastasis et al. 2008) as part of bioeconomy development.

Climate change adaptation can be addressed in several different ways by means of agroforestry. Thus, shading and cereal variety selection to shade may be useful to maximise crops resilience in those areas where extremely high temperatures are becoming more frequent. Moreover, certain shadow amount when cereals are cropped ease the reduction of weeds and therefore limit pesticides use since annual herbaceous weed species are more initially light-demanding than cereal crops. The reduction of weeds through tree shadowing techniques may even boost cereal crops production over open sites production by diminishing the competitiveness factor. Silvoarable practices are recognized in most of the RDP of the Mediterranean basin where landscape features associated to i) establishment, maintenance and restoration in Italy, ii) restoration and management in Spain and iii) management in France, are promoted through different measures. French tradition of landscape features management (Mosquera-Losada et al. 2018a and b) underweight restoration and establishment measures necessity but sharpen maintenance requirements. Measure 4.4 associated to the investments in physical assets is predominantly applied to establish or restore already existing landscape features (i.e. copses, hedgerows, trees in line….) while the agri-environment measure 10.1 is mainly linked to the maintenance of the landscape features, as a consequence of the recognition of the ecosystem services this systems deliver (water management, erosion…).

Despite the noted benefits and the promotion of silvoarable practices in Europe, the extent of this type of land use is indeed low. Technical knowledge already existing in research should be transferred to farmers to promote silvoarable practices in Europe as claimed by the aforementioned 900 stakeholders that took part in the AFINET project activities (AFINET 2018). Therefore, funds to promote extension services, demonstration fields and living labs are essential to foster the transition from intensive to extensive livestock systems as highlights the policy report of AFINET (2020). Intensive farming systems are based on the decapitalization of soils and extensive use of resources, being mostly produced at a great distance from the targeted agricultural lands, generating waste of non-renewable energy. On the hand, cropland farming systems based on silvoarable practices capitalize the soil, as organic matter is introduced in deeper soil layers and nutrients are recycled thanks to the deep roots of the trees and shrubs (Mosquera-Losada et al. 2011, 2015). Therefore, the use of hedgerow biomass residues as a source of organic matter is one of the multiple possibilities agroforestry provides to increase the natural capital resource of the soils in the agricultural lands. Roos decomposition in deeper soil layers prevents from organic matter mineralization when ploughing is performed, being also a good way to comply with sustainable initiatives such as the "4 per 1000" initiative (Four per thousand 2020). Considering all the aforementioned, an opportunity to be explored in the next CAP surges since agroforestry provides nature-based solutions to recover degraded soils that were not sustainably used. In this context, agroforestry can be interpreted as a land use practice but also as a farm and landscape system, being a useful tool to favour the integration of different land uses in a biogeographic region in which vegetation growth rate is slow. Moreover, the reduced natural productivity per unit of land of agricultural lands in the Mediterranean, usually associated to a larger farms size, can be overcome if the delivery of more products per unit of land is achieved through an adequate integration of woody perennials that enhance organic matter recycling. Again, the adequate promotion of value chains is key based on the search for alternative uses of the woody component currently unused and the adequate establishment of value chains within the frame of the updated bioeconomy European strategy (EC 2018b, c and d). In addition, the adequate provision of initial infrastructures based on the business plans development and the establishment of adequate extension services, seeking to promote environmental preservation alternatives, are recommended to be approached.

The need of integrating agroforestry silvopastoral practices in the Mediterranean olive orchards is linked to the intensive farming conducted in the last decades resulting in important soil erosion and degradation that can be recovered by sowing pasture under the trees. Livestock grazing increases the preservation of the olive soil stands, being a sustainable way to reduce competition with trees while favouring nutrient recycling through their faeces and urine deposition. Bearing this in mind and acknowledging livestock integrated systems, Andalucia has developed measures to increase farmers knowledge on silvopasture systems with both permanent crops and woodlands (to reduce forest fire risk) including demo sites and farmers and advisor assessment as highlights the EIP-Agri (2017) innovation development schemes. Agroforestry demo-sites creation linked to the RDP was also carried out by the Baleares where nut trees are dominant. The islands of the Mediterranean region present significant variability in the share of land use cover, ranging from the ones with a high anthropogenic impact (Sicily) to those with a lower impact (Sardegna or Corsica). Thus, in Sicily it is still possible to find agroforestry areas as traditional cultural landscapes (Cullota and Barbera 2011) heritage of a long tradition in olive trees agroforestry that fades nowadays due to land abandonment (Ruhl 2011). On the contrary, Sardinia has conducted to a clear reduction of silvopasture practices and an increase on forest lands. A similar situation with agroforestry practices to forest land transition can be found in Corsica (Vella et al. 2019), Cyprus (Hellicar et al. 2019) and Baleares especially linked to nut production. As a consequence, agroforestry policy measures in the Mediterranean areas are associated with demo sites and forest fire prevention techniques in Baleares and forest and agri-environment measures in Sicilia and Sardegna. Besides, value chain promotion operates as a RDP measure in Sardegna.

Related to woody perennials in silvoarable practices, no measures linked to its bioeconomy were found. Instead, the current CAP promotes activities associated to the introduction, restoration and maintenance of woody perennials (landscape features) in arable lands as a mechanism to enhance environment deliveries (Mosquera-Losada et al. 2018a, 2018b; Santiago-Freijanes 2018a, 2018b, 2018c). For better performance, CAP should be integrated by measures associated to social aspects in the light of bioeconomy promotion through farmers cooperativism upgrading, but also the adequate development of value chains involving multiple products and life cycle assessments that support a reduction of non-renewable energy resources consumption.

For this, CAP promotion should bear in mind that public and private areas as public lands are not eligible to receive CAP direct payments.

Sewage sludge outstands as a highly suitable instrument to drive circular economy forward in agroforestry systems and fulfil the three dimensions of sustainable development, environmental, social and economic (FAO, 2014). Furthermore, silvopastoral systems complement and optimize this positive assessment on sewage sludge addition providing i) environmental beneficial effects as carbon sequestration and biodiversity enhancement due to the livestock grazing positive aspects ii) social benefits through circular economy turning residues into natural resources and iii) economic positive return generating more possibilities in the same extension of land when compared with traditional systems since timber, livestock, forest farming and other outputs as bee-keeping products are potential interrelated sources of incomes. As an additional confirmation of the widely reported benefits of silvopastoral systems, the conducted experimental study outcomes strengthen the advantages and keys of hazards-limiting management of an organic fertilized system. Thus, trees height observed in the last year of this experiment (15.95-19.82) was within the range established by Sánchez-Rodríguez et al. (2003) in Galicia for an age of 20 years in the II (15-19 m) and III (19-23 m) site-quality classes. Moreover, the tree dominant height was higher than those found in other silvopastoral systems established under P. radiata but fertilised with lower SS doses (50 and 100 kg total N ha-1) than the ones applied in this study (Mosquera-Losada et al., 2011a). Thereupon, tree height was generally higher when the lime and organic or inorganic fertilisers, were applied into the soil compared with the no fertilisation treatment, independently of the SS doses acknowledging the results previously described by numerous authors asserting that management practices such as liming and organic and inorganic fertilisation enhance the chemical and physical soil properties and therefore boost tree growth (Ferreiro-Domínguez et al., 2014; Mosquera-Losada et al., 2012; Saarsalmi et al., 2011). These positive results did not found, at the moment, a supportive response and subsequent implementation probably due to the investment needed and lack of proper policies encouragement of this circular economy based activities.

While the tree's growth could benefit from liming and fertilisation, no significant effect of the treatments was found on canopy closure probably due to its early occurrence, being this factor similar in all types of treatments consequence of the high competition among trees. On the other hand, a clear influence of the tree growth and the subsequent canopy closure was observed on the variation of the soil pH and the SOC (Soil Organic Carbon) over time. The highest pH values observe barely reached up to 5.3, pointing out that this experiment was established in very acidic soil (Andrades and Martinez, 2014) probably resulting from the parent rock material, the acidification usually caused by conifers, and the Galician rainfall regime characterised by high precipitation rates during most of the year (Álvarez et al., 2002) and subsequent cations extraction. Galician climate conditions, favoured by more average hours of light than northern European countries and generous precipitation rates, boost biomass production, which intensifies the uptake of nutrients from the soil and, on the other hand, facilitate the cations leaching through the soil profile and, therefore, contributes essentially to the natural acidic trend of the soils in this region (Álvarez et al., 2009; Macías et al., 1978). However, the significant correlation found in this experiment between soil pH and tree dominant height suggests that the uptake of soil cations by trees was the main driver of soil pH downtrend over lime and SS addition. The negative effect of fast-growing conifer plantations on soil pH was previously observed in afforested areas with Pinus nigra Arnold (Adams et al., 2001) and in silvopastoral systems also established under P. radiata (Giddens et al., 1997). Moreover, probably both the liming and the fertilisation with SS performed in this study stimulated the N mineralisation by reducing the C/N relationship (Whitehead, 1995) which sharpen the uptake of cations by the trees and the understory vegetation narrowing the beneficial effect of liming and SS on the soil pH (Mosquera-Losada et al., 2006). Circular economy emerges as a realistic option being strengthed by sewage sludge performance in this study related to pH management practices. Thus, while the beneficial effect of lime on soil pH decreased in the medium and long term, the beneficial effect of the SS on soil pH was maintained throughout the study (Mosquera-Losada et al., 2012), mainly when high doses of SS (S3 - 480 kg total N ha−1) were applied in comparison with the mineral and the no fertilisation treatments. The positive effect of the fertilisation with SS on soil pH could be explained by the Ca input into the soil (Tsadilas et al., 1995). The appreciated negative effect of the higher doses of SS compared to the lower one (S1 - 160 kg total N ha−1) may be explained by to the incorporation constraints of the high doses of SS into the soil but also the higher pasture production obtained when the soil was fertilised with medium (S2 - 160 kg total N ha−1) and high doses of SS since low doses do not improve soil conditions, remaining very poor, as happened in 2001 (Mosquera-Losada et al., 2012). On the other hand, the lower production of pasture associated to low fertilization doses at the beginning of the study (Mosquera-Losada et al., 2012) probably had an early positive effect on tree dominant height, which was maintained until the end of the study. A conclusion can be drawn in order to maintain an adequate range of soil pH. Thus, the application of additional amendments with higher pH than soil (lime, sewage sludge) is advisable in the middle years of the tree plantation to compensate the extractions of the different cations by the trees and the acidifying effect promoted by the deposit of acidifying materials from trees such as pine needles, as a consequence of canopy closure (Fisher and Binkley, 2012).

Soil organic carbon (SOC) is a key element that silvopastoral systems management can deal with, , in order to promote climate change adaptation and mitigation by fostering carbon sequestration and storage. Considering the aforementioned, the values found in this experiment were similar to those described in previous studies developed in the same area (>12.08%) in which more than seven thousand soil samples were analysed under different land uses in Galician area (Anta et al., 2015). This area is characterized by high SOC content as a consequence of large OM inputs from the vegetation since warm temperatures and adequate water availability throughout the year turns Galicia in the region of Europe with the highest forest growth rates. The high OM inputs together with the low soil pH of this area promote hight content of OM in soils when compared with other Spanish areas where climate conditions limit biomass incorporation, as the main C source in terrestrial ecosystems, and high pH favours the incorporation and mineralization of the OM in the soil (Howlett et al., 2011). There was a similar pattern with pH and SOC in the conducted silvopastoral system experiment over time. Thus, the variation of the SOC was found to be related to the tree age and the subsequent canopy closure but also of the weather conditions. Thereby, at the beginning of the study, when the influence of the tree canopy was low, a negative effect of liming and fertilisation with SS on the levels of SOC was observed. However, from 1999 to 2006, the SOC increased probably due to the pasture establishment as a major soil OM source from roots and senescent material (Mosquera-Losada et al., 2011b) but also as a consequence of SS application in soil (Dai et al., 2017), particularly the larger doses (S3). Furthermore, the application of SS to the soil probably implied higher inputs of OM (needles) into the soil surface in comparison with the no fertilisation treatment since tree growth better performed in the SS treatments (Mosquera-Losada et al., 2012). As a highlight, the increase of the SOC levels and soil pH associated with SS fertilization in comparison with NF treatment brings to light the potential of this type of waste as an important source of nutrients, contributing to the bioeconomy (EC, 2018) and circular economy (EC, 2020) concepts of the European Commission. On the other hand, when tree canopy reached the closure (year 2006; >96%), the SOC generally decreased to the end of the experiment despite pine needles falling to the soil surface. This could be explained because the conditions of temperature, humidity, and aeration in the understory probably were negatively affected by the tree canopy development which reduced the soil biota activity and therefore the incorporation of the fallen pine needles into the soil (Pérez-Batallón et al., 2001). Canopy closure from 2006 modified the understory composition being vegetation replaced by fallen pine needles characterized by a slow decomposition rate if compared with the leaves of broadleaves species (Rigueiro-Rodríguez et al., 2012). The significant correlation found in this study between SOC and tree canopy cover indicates that the tree canopy cover development influenced SOC by modifying crucial processes such as the incorporation and mineralization of the needles (OM) soil inputs (Gallardo,2003; Rousk et al., 2009). The study outcomes can be related to the importance of management activities (pruning, clearing or thinning) as a mean to enhance soil biota activity and, therefore, increase the incorporation of the OM into the soil, favouring nutrients recycling in the system and soil C sequestration (Nair et al., 2010), which is in line with IPCC (2019b) recommendations to promote mitigation efforts to fight climate change. In this context, the next Common Agricultural Policy (CAP) 2021-2027 will include the eco-schemes, as mandatory schemes for Member States and voluntary for farmers, to promote environmental and climate supportive actions such as SOC sequestration through direct payments from Pillar 1 of the CAP (Meredith and Hart, 2019). According to this and the results obtained in this study, as levels of SOC varied depending on weather conditions variability, control plots should be established to check if the managed plots by the farmers increase the SOC compared with the unmanaged plots, regardless of the weather conditions, in order to account the benefit of the practices. Eco-schemes deliver a innovative opportunity to care for the environment and climate, thus supporting the transition towards more sustainable farming systems and contributing to the net-zero emissions in the agriculture sector in 2050 (Lóránt and Allen, 2019), which should start in the post 2020 CAP.

Conclusions

1.- The Mediterranean area of Europe is being dominated by the antropogenic pressure which has been modified in the last century after the green revolution causing intensification in some areas but also land abandonment in the last decades. This makes that most of the agroforestry practices (both silvopasture and silvoarable) are placed in the West Mediterranean area of Europe in the west provinces of Spain and Portugal.

2.- Land abandonment as well as the afforestation and reforestation policies caused a recovery of oaklands in the Mediterranean areas, whose understory is increasing and causes a lot of policy challenges related with forest fires that became exhacerbated by climate change.

3.- Olive trees are the most representative woody perennial when agroforestry is implemented in arable lands associated to silvoarable practices to optimize the use of nutrients but also to protect soil erosion increasing the sustainability of olive orchards.

4.- Oaklands are the most important woody perennial when agroforestry is implemented as silvopasture to extend the grazing period as a result of the benefit they cause in pasture production and as a feed resource (acorn) However, most of the regions have a low extent of silvopasture and can be linked to a high (intensive agriculture) and low (abandonment) anthropogenic pressure.

5.- Conifers are also dominated in some Mediterranean regions, but the extent on agroforestry in these areas is rather low, because as pioneer species, pines are planted in marginal areas with low productivity to feed livestock and they do not provide extra feed to livestock systems such as the oaks (acorns).

6.- The potential extent of silvoarable agroforestry practices delivering ecosystem services in the Mediterranean area of Europe is enormous because of the reduced currently extent that this sustainable land use system has.

7.- Silvoarable practices should be promoted by the CAP considering the promotion of the extension services activities but also the development of adequate supply and value chains within The Farm to Fork and EU Bioeconomy Strategy to fulfil the European Green Deal promoted by the European Commission.

8.- Most of the silvopasture measures related with silvopasture are adapted to the local necessity, mainly associated to regeneration and maintenance in the managed dehesas but linked to forest fire prevention through silvopasture promotion in the majority of the Mediterranean regions of Europe.

9.- The benefits that agroforestry provides are generally acknowledge in most of the Mediterranean area of Europe where policy foster their maintenance of the establishment, however the budget allocated to these policy measures is rather small. Most of agroforestry practices implemented in arable lands are linked to landscape features funded through the implementation of the agro-environment measure 10.1.

10.- The large set of ecosystem services that agroforestry provides is key for the European transition towards more sustainable land use systems, which makes necessary to promote agroforestry and circular economy linked to sewage sludge through the implementation of living labs, increase of technical knowledge among farmers, to provide tools to compare the best business options including the development of value chains for woody perennial products, as well as to develop knowledge systems associated to adequate extension services where research experiments as well as innovative farms can be used to spread the agroforestry. Tools linked to foster extension services, operational groups and eco-schemes associated to agroforestry should be promoted in the post 2020 CAP. An updated regulation related with sewage sludge is needed.

11.- Agroforestry is an intensive farm use system that increases biomass production per unit of land therefore it should be linked to a higher fertilizer use, that can come from urban areas as, for example, sewage sludge. Sewage sludge improves tree growth and therefore increases biomass production per unit of land thanks to the increase of soil fertility it causes if adequate doses, indeed below the heavy metal contamination potential, are used. However, sewage sludge is not currently promoted to be use as fertilizer due to the lack of understanding of its potential.

12.- The use of sewage sludge positively affected tree growth as the tree was benefited from the very beginning when its growth rate was very high, however, the extraction of cations was not compensated by the early sewage sludge addition and increased soil acidity in an area where rainfall and rock parent material make soils to become acidic. This suggests that tree growth may be benefited from additional sewage sludge application mostly with low doses.

13.- Our results shos that it seems advisable to apply additional amendments with higher pH than the soil (lime, sewage sludge) in the middle-ending years of the tree plantation to maintain adequate ranges of soil pH and SOC to compensate for the cation extractions by trees.

14- Tree growth increase cations extraction from soil and modifies the understory microclimate which decreased the levels of soil pH and SOC in the soil over time. However, a positive effect of the fertilisation with SS on soil pH and SOC is observed, mainly in the case of the high doses of SS on pH, which did not compensate for the cations extraction from the soil by the trees, mainly in the years after the application of SS into the soil. Tree age and canopy closure is the main driver to increase soil carbon in the soil.

15.- The levels of SOC varied depending on weather conditions variability, control plots should be established to check if the managed plots by the farmers increase the SOC compared with the unmanaged plots, regardless of the weather conditions in order to account the benefit of the practices. Eco-schemes deliver an innovative opportunity to care for the environment and climate, thus supporting the transition towards more sustainable farming systems and contributing to the net-zero emissions in the agriculture sector in 2050, which should start in the post 2020 CAP.

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