MARVIC

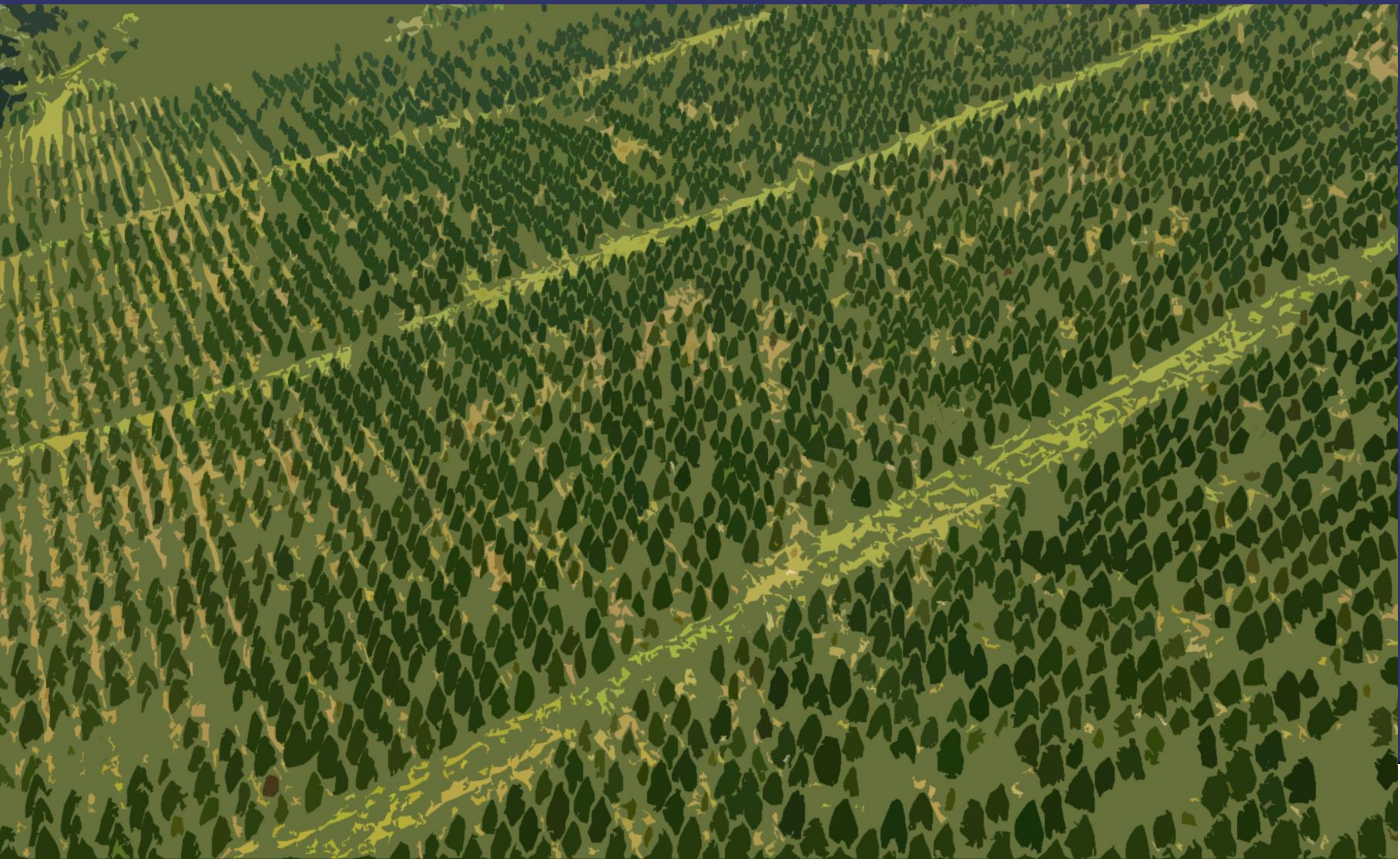
MRV for carbon farming

Funded by the European Union

# Carbon Farming Mitigation Potential: Evaluating the mitigation potential (and uncertainties) of carbon farming practices

MARVIC

Deliverable 4.1



# Document Information

| Grant agreement | 101112942 |
|---|---|
| **Project Title** | Developing and testing a framework for the design of harmonized, context-specific Monitoring, Reporting and Verification systems for soil Carbon and greenhouse gas balances by agricultural activities |
| **Project acronym** | MARVIC |
| **Project duration** | 48 months |
| **Coordinator** | Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Belgium |
| **Related work package(s)** | WP4 |
| **Related task(s)** | T4.1 |
| **Lead organisation** | Spanish National Research Council (CSIC) |
| **Author(s)** | Milagros TORRÚS CASTILLO (CSIC), Jorge ÁLVARO FUENTES (CSIC), Laura MARTINEZ GARCÍA (CSIC), Jana POLÁKOVÁ (CZU), Adam SVOBODA (CZU), Jens LEIFELD, Elena LARYSCH (ALU-FR), Paul PARDON (ILVO), Caroline DANKERS (WR), Jan Peter LESSCHEN (WR), Ioanna PANAGEA (ILVO) and José Alfonso GÓMEZ CALERO (CSIC). |
| **Contributors** | Hui XU (ILVO), Flora DESMET (WBF). Greet RUYSSCHAERT (ILVO) |
| **Due date** | M18 |
| **Submission date** | |
| **Dissemination level** | Public |

# Document Revision History

| Date | Version | Submitted by | Reviewed by |
|---|---|---|---|
| 13/12/2024 | 1.0 | Milagros Torrús Castillo (CSIC) | Ioanna PANAGEA (ILVO), Caroline DANKERS (WR), Jan Peter LESSCHEN (WR). |

| | | | |
|---|---|---|---|
| 30/04/2025 | 1.1 | Milagros Torrús Castillo (CSIC) | Jan Peter LESSCHEN (WR), Greet RUYSSCHAERT (ILVO), Hui Xu (ILVO) |

Report DOI: 10.5281/zenodo.14357697
Dataset DOI: 10.5281/zenodo.14408832

**How to cite this report:**

Torrús Castillo M., Álvaro Fuentes J., Martinez García L., Poláková J., Svoboda A., Leifeld J., Larysch E., Pardon P., Dankers C., LESSCHEN J. P. , Panagea I. and Gómez Calero J. A. (2024). Carbon Farming mitigation potential: Evaluating the mitigation potential (and uncertainties) of carbon farming practices (Deliverable 4.1 of MARVIC project, v1.0; p111)

**Disclaimer**

# Contributing partners

| Participant organisation name | Short name | Country |
|---|---|---|
| **EIGEN VERMOGEN VAN HET INSTITUUT VOOR LANDBOUW- EN VISSERIJONDERZOEK** | ILVO | BE |
| **STICHTING WAGENINGEN RESEARCH** | WR | NL |
| **CESKA ZEMEDELSKA UNIVERZITA V PRAZE** | CZU | CZ |
| **AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS** | CSIC | ES |
| **ALBERT-LUDWIGS-UNIVERSITAET FREIBURG** | ALU-FR | DE |
| **EIDGENOESSISCHES DEPARTEMENT FUER WIRTSCHAFT, BILDUNG UND FORSCHUNG** | WBF | CH |

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# Executive Summary


### Purpose

This deliverable (D4.1) evaluates the mitigation potential and associated uncertainties of carbon farming (CF) practices across five key agricultural systems: woody crops, peatlands, arable lands, grasslands, and agroforestry. It supports the MARVIC project's aim of developing harmonised, context-specific Monitoring, Reporting and Verification (MRV) systems that align with the objectives of the EU Mission Soil and the Carbon Removal and Carbon Farming Certification (CRCF) Regulation. The report compiles scientific evidence to inform the design of effective mitigation strategies across diverse pedoclimatic and land management contexts.

### Intended Audience

This report is intended for EU and national policymakers, land-use planners, environmental managers, and researchers in agriculture and climate change mitigation. It also targets practitioners and stakeholders implementing or advising on CF practices, especially those developing MRV tools and frameworks.

### Description of the Main Activities

The report is based on extensive literature review and meta-analyses. Where published meta-analyses were available (e.g. arable land), they were leveraged; otherwise, new analyses were conducted (e.g. woody crops). The analysis examined carbon dynamics, including SOC content and stocks, biomass carbon, and GHG emissions, alongside ecosystem co-benefits.

Scientific publications and datasets from EU-funded and national research projects were used, e.g. EJP Soil CarboSeq. Management practices were grouped for comparability, and practices were analysed across systems using standard metrics where possible. Limitations due to data scarcity and methodological inconsistency were documented and evaluated.

### Key Results

Result 1: SOC gains are maximised through specific CF practices.

Practices like no-tillage, organic amendments, and cover cropping increased SOC stocks in most systems, particularly in olive groves and vineyards. The combination of no-tillage, pruning residue mulching, and cover crops yielded the highest SOC concentrations.

Result 2: Peatland rewetting has substantial mitigation potential.

Rewetting significantly reduced $CO_2$ emissions and enhanced carbon stability. However, insufficient data on $CH_4$ and $N_2O$ fluxes, and dissolved organic carbon (DOC), limits full evaluation of long-term outcomes.

Result 3: Agroforestry systems deliver high and stable carbon storage.

Silvoarable systems showed higher carbon sequestration than silvopastoral systems, especially in alley cropping. Hedgerows displayed greater—but more variable—sequestration potential. Management intensity influenced the sequestration outcomes significantly.


Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Result 4: Grasslands support both mitigation and biodiversity goals.

Improved grazing management, reseeding, and conversion from arable land to grassland led to notable SOC gains and ecosystem benefits. SOC stocks were highest under permanent grassland and organic inputs.

Result 5: Arable land benefits from reduced tillage and rotations.

Zero tillage had the highest SOC sequestration potential in arable systems, however most studies focused on topsoil, which will overestimate the potential, as several studies showed decreasing SOC stocks in the subsoil. Cover crops and organic amendments also contributed substantially to soil carbon sequestration, particularly when combined with improved crop rotations.

**Research and Practice Implications**

These findings highlight the need for long-term, standardised field studies capturing full soil profiles and reporting management history. SOC responses varied by depth, system, and management intensity. Co-benefits such as erosion control, improved soil health, and biodiversity enhancement were commonly associated with CF practices, especially under olive groves and vineyards.

Enhanced collaboration is needed to harmonise methodologies and facilitate meta-analyses across pedoclimatic gradients. Integration of below-ground biomass data for agroforestry systems and GHG flux measurements for peatlands remain essential.

**Policy Implications**

Policy interventions should prioritise agroecological approaches that enhance SOC sequestration, reduce GHG emissions, and improve resilience, such as cover cropping, agroforestry, and peatland rewetting. Tailored incentives, capacity building, and long-term funding mechanisms are key to supporting CF adoption. The results also show a large variability, which implies the need for the development of region-specific policies to align mitigation strategies with local socio-economic and environmental contexts.

**Conclusion**

D4.1 provides robust evidence on the mitigation potential of diverse carbon farming practices, identifying strategies and key knowledge gaps. The findings will inform the development of reliable MRV systems and guide future research, supporting EU climate targets and sustainable agriculture objectives.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# Table of Contents

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# List of Tables

# List of Figures

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# Acronyms and Abbreviations

**AFS:** agroforestry systems

**CF:** carbon farming

**DOC:** dissolved organic carbon

**GHG:** greenhouse gases

**GWP:** global warming potential

**MRV:** monitoring, reporting and verification

**NEP:** net ecosystem productivity

**NT:** no tillage

**SOC:** soil organic carbon

**SOM:** soil organic matter

**TOC:** total organic carbon

**WT:** water table

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# 1. Introduction

This deliverable (D4.1) presents the main outcomes of Task 4.1: *State of the art on mitigation potential of carbon farming practices.* It identifies and evaluates the mitigation potential and uncertainties of carbon farming (CF) practices across five key agricultural systems: woody crops, peatlands, arable lands, grasslands and agroforestry. Its goal is to assess these systems' capacities for carbon sequestration, reduction of greenhouse gas (GHG) emissions, and broader environmental benefits. This work aligns with the main goal of MARVIC to develop context-specific, harmonised Monitoring, Reporting, and Verification (MRV) systems for CF, supporting EU Mission Soil objectives and the Carbon Removal and Carbon Farming Certification (CRCF) Regulation. The results are discussed in relation to the specific objective of Task 4.1, which were mainly to:

**1-** develop a database of relevant and suitable CF practices for arable land, grassland and perennial crops on mineral soils, organic soils, and agroforestry (including woody landscape elements).
**2-** provide an appraisal of the potential of these CF practices in increasing carbon sequestration in these systems, including a discussion on the uncertainty of these mitigation potentials.
**3-** identify the technical and biophysical factors that constrain the theoretical mitigation potential of each CF practice.
**4-** detect the main gaps in knowledge on evaluating the actual effectiveness of these CF practices.
**5-** compile studies, datasets and situations that might be of relevance to the development and testing of MRV systems for CF.
**6-** specify the links among the CF practices and other co-benefits in the provision of ecosystem services.

The methodologies include a thorough literature review and meta-analysis, focusing on the diversity of soil types, climatic zones, and land-use practices worldwide. Where possible, we prioritised the studies with a European focus to ensure the data are as closely relevant to EU policy-makers. However, for certain systems, the substantial variability among the reviewed studies, particularly with respect to management practices and, in some instances, the absence of sufficient or relevant information to develop a comprehensive understanding of the subject, it was considered necessary to include all available and pertinent studies globally, where appropriate.

At the global scale, significant differences in climate and edaphic conditions cross regions such as the United States, broader North America, South America, China, and Australia greatly influence the implementation and effectiveness of carbon farming practices compared to those in Europe. For instance, the United States and Australia often operate under more arid or semi-arid conditions, where large-scale conservation tillage, rotational grazing, and cover cropping are widely applied and adapted to extensive land areas with lower soil organic matter. In contrast, tropical and subtropical regions of South America face challenges related to high decomposition rates and

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

nutrient-poor soils, leading to the adoption of agroforestry systems and integrated crop-livestock management to enhance carbon retention. China's agricultural systems, shaped by intensive cultivation and diverse climatic zones, have increasingly incorporated practices like straw incorporation and reduced tillage to mitigate carbon loss. Meanwhile, Europe's temperate climate, more fragmented landscapes, and historically intensive land use demand tailored approaches such as compost application, diversified crop rotations, and reduced inputs. Excluding studies from outside the European context would have limited the robustness of the analysis, particularly in light of existing data constraints and the variability in available literature across regions.

For the reviews, the team capitalised the available results obtained from ongoing projects such as the EJP SOIL CarboSeq, and data from networks, e.g. the Baltic Sea Field Observatory Network and national projects. This analysis considered five different agricultural systems, described as follows.

The first system is woody crops that covers around 8% of the agricultural area of the EU (EUROSTAT, 2024). Woody crops have been identified as an agricultural system with high potential for CF due to their life span from decades to centuries, and the possibility of implementing agronomic practices, like temporary or permanent cover crops, with a positive effect on CF and other co-benefits (Vicente-Vicente et al., 2016). Although present in all EU countries, the highest share of woody crops in the EU is concentrated in the Mediterranean member states (EUROSTAT, 2024).

The second system is peatland. Peatlands are a type of wetland characterised by the accumulation of organic matter, such as sphagnum moss, which forms peat. Peatlands cover around 2-3% of the total land area in the European Union (EUROSTAT, 2024) although their distribution varies widely among member states. Countries in Northern Europe, such as Finland, Sweden, Ireland, and Estonia have the largest peatland areas.

The third system is field or arable crops. These typically include cereals, such as wheat and barley, oilseeds (e.g. rapeseed), legumes (e.g. peas) and root crops, such as potatoes and sugar beets. These crop areas cover about 60-65% of the agricultural land in the EU (EUROSTAT, 2024) and are well distributed across all the member states.

The fourth system is grassland, which includes both permanent grassland and pastures. It is defined as land primarily used for grazing livestock or for hay production. Grasslands account for approximately 30-35% of the total utilised agricultural area in the EU, with a higher proportion in the northwestern European countries like Ireland and France, and some central European countries like Austria, Slovenia or Luxembourg. Mediterranean countries and some central European countries like Hungary or Poland have a lower grassland area (EUROSTAT, 2024).

The fifth system covered is agroforestry, which considers all systems integrating trees and shrubs into agricultural landscapes. It includes various approaches such as hedgerows, silvopasture, alley cropping, and other forms of tree-based agriculture (Sonja et al., 2019). Agroforestry covers about 3-5% of the total agricultural area in the EU, with the extent of agroforestry varying widely across member states. It has a higher extension in southern and western Europe, while it is less used in northern and central European countries (EUROSTAT, 2024).

# 2. Woody crops

*Milagros Torrús Castillo[1], Jorge Álvaro Fuentes[1], Laura Martinez García[1], José Alfonso Gómez Calero[1].*

*[1]Spanish National Research Council (CSIC), Spain*

## 2.1. Methodology for information search.

The bibliographic review of peer-reviewed research studies on woody crops was carried out using the core Web of Science Core Collection for the period 2000-2023. Relevant existing papers with experimental information, as well as meta-analyses studies were compiled. Woody crops were grouped into the following subsystems: almond trees, vineyards, olive groves and fruit trees. Within the fruit tree subsystem, the following were considered: citrus orchards (lemon, orange and mandarin orchards), wolfberry, pomegranate, peach, nectarine, apple, tree nuts and mango orchards.

For each subsystem we used specific keywords and criteria (see Table 1 with the example for the vineyards subsystem). Annex 1.A. contains the keywords and connectors used for the search for the other three woody crops subsystems.

**Table 1.** Keywords and connectors used for the search for the vineyard subsystem.

| |
|---|
| Carbon sequestration in vineyards *OR* Carbon sequestration and vineyards<br>*OR*<br>Carbon farming and vineyards *OR* Carbon farming in vineyards<br>*OR*<br>Nature based climate solutions in vineyards<br>*OR*<br>Agro-environmental practices and organic carbon and vineyards<br>*OR*<br>Carbon sequestration and vineyards and sustainable practices *OR* Sustainable practices and carbon sequestration and vineyards *OR* Organic carbon and sustainable practices and vineyards *OR* Sustainable practices and vineyards and carbon *OR* Sustainable practices and olive vineyards<br>*OR*<br>Cover crops and carbon sequestration and vineyards *OR* Cover crops and carbon and vineyards<br>Pruning residues and carbon and vineyards *OR* Pruning residues and carbon sequestration and vineyards<br>*OR*<br>Compost and carbon sequestration and vineyards *OR* Compost and carbon and vineyard<br>*OR*<br>Tillage and carbon sequestration and vineyards *OR* Tillage and carbon and vineyards<br>*OR*<br>Emissions and vineyard and management practices *OR* Emissions and carbon sequestration and vineyards *OR* Warming potential and carbon sequestration and vineyards |



Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

The original search resulted in more than 500 articles, which were screened first by their title and abstract. After this, the selected articles were read to identify those that contained quantitative data.

Those articles that presented quantitative data on the variables that we considered key for the analysis were selected. The total number of papers found for the case of the almond subsystem was 18, of which 13 were retained, since they focused on the stability of the aggregates, soil properties and economic aspects. The remaining presented an overview of the advantages of using spontaneous cover crops, but without reporting quantitative data. In the case of fruit orchard category, 29 papers were found, however 21 were retained, since they focused on soil properties, especially water content or enzymatic activities. In the vineyard subsystem, there were 89 papers, of which 48 were retained, since they focused on the analysis of the life cycle, ecosystem services, soil microbiology, the nutritional aspects of the harvest or economic aspects. Finally, for the olive groves subsystem there were a total of 92 papers, and 48 were retained, whose topics focused on the measurement of carbon within soil aggregates or on sociology without providing experimental data, economic analysis, soil properties or analysis of the life cycle.

## 2.2. Management considered

The main management practices identified in the review for each woody crop subsystem were:

- Almond orchards: intercropping, tillage, reduced tillage, cover crops and green manure.
- Fruit orchards: mulching (pruning residues, straw, grass clover, wood chips and shredded paper), organic amendment (compost), spontaneous or sowing cover crops, tillage and no tillage (NT).
- Vineyards: organic fertilisers and manure (biochar, cattle or mushroom compost), tillage, NT, spontaneous cover crops or sowing cover crops and pruning residues.
- Olive groves: tillage, NT, spontaneous cover crops or sowing cover crops, organic amendment (olive leaves and “alperujo”, a paste resulting from the extraction of olive oil, i.e. pomace and olive pomace pastes), livestock-grazing (sheep), pruning residues and bare soil.

The literature shows that in most cases, different management practices are used in combination. For instance, in almond orchards tillage was combined with the use of green manure or in fruit orchards different tillage strategies (from NT to periodic ones). In vineyards it was also common to combine different tillage strategies with cover crops, while in olive groves combining tillage with application of organic amendments.

A summary of the most widely reported management practices that influence the storage of carbon in the soil in woody crop systems are: **i)** spontaneous cover crops or sowing cover crops; **ii)** reduced tillage; **iii)** the use of amendments or organic fertilisers; **iv)** the use of chopped pruning residues as a mulch on the soil; and **v)** low intensity grazing by livestock of cover crops.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

To cope with the large number of possible management combinations in the study cases and the limited number of experimental studies, it was decided for the purpose of statistical analysis to summarise the management practices in the following groups: cover crops, manure or organic fertilisers, NT and tillage (used as a reference), and a combination of these.

## 2.3. Variables used

Our review tried to identify the available information on the biogenic carbon (carbon that is sequestered from the atmosphere during biomass growth) flows in woody crops. Hence, the variables selected from each article were focused on the soil and the above- and below-ground crop biomass.

The variables taken into account in the bibliographic search were:

**i)** soil related category: total organic carbon (TOC), SOC mineralisation rate, carbon stock, organic carbon concentration, bulk density, soil organic matter (SOM), soil respiration and soil microbial biomass.
**ii)** biomass related category: the dry weight of the aboveground biomass (trunk, leaves, branches, fruit, canes, among others, and including the amount of pruning residues, spontaneous cover crops or harvest) and the dry weight of the? below-ground biomass, and the carbon associated with these components.
**iii)** emissions related categories, the following variables were taken into account: $CO_2$, $N_2O$, $CH_4$ emissions derived from agricultural activities, carbon footprint and carbon balance.

Not all variables were present in the articles reviewed. Most focused-on soils, while few focused on above- and below-ground biomass and the carbon stored in crop biomass. The same occurred in the case of variables related to GHG emissions or global warming potential (GWP). Therefore, the information contained in the database was filtered, and the variables with the greatest representativeness in all systems were selected. These were:

1) SOC concentration (g C/kg soil).
2) SOC stock (Mg C $ha^{-1}$)
3) For vineyards the carbon that accumulates in above- and below-ground biomass (Mg C $ha^{-1}$).

## 2.4. Analysis

Once the information collected in the database, it was filtered by the three categories noted earlier: **i)** soil, **ii)** biomass and **iii)** emissions, and converted into homogenous units. In some cases, carbon stock was calculated taking into account the carbon content, the bulk density and the sampling depth provided in the article.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

The GHG emission and biomass categories, with the exception of vineyards, were discarded due to the limited number of data available for analysis. Only four out of 21 selected articles on fruit trees contained information on the biomass, while in almond trees it was two out of 13. Within the olive groves and vineyards, only 4 and 15 of the 48 selected articles, respectively, focused entirely on the carbon accumulated in the above- and below-ground biomass. Therefore, the carbon accumulated in the different parts of the vineyards (Mg C $ha^{-1}$) was analysed: in their above-ground biomass (stem, branches, leaves, canes and fruit) and below-ground biomass (roots), as well as in the pruning wood and cover crops. In turn, the carbon accumulated in the different parts of the crop was also collected considering the age of the plant (5, 10-15 and 20-35 years).

A large variability in terms of soil characteristics, climate, age of cultivation and the combination of various management practices, among others, was noted within the soil category. As a result, and due to their interacting nature, it was difficult to discriminate between individual variables (soil characteristics, climate, age, among others). After this screening a first appraisal was made by analysing the soil carbon stock and soil carbon content for each subsystem (vineyards, almond trees, fruit orchards and olive groves). This was done in two steps. First, we considered all the existing data for all sampling depths, and grouped them by the predominant management practices, namely cover crops, manure or organic fertilisers, NT and tillage, which was used as control. In this analysis, all depths and horizons were detected. That is, if the article analysed a variable considered for depths of 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-25 cm up to 100 cm depth, all data at these depths were considered, not just one value from 0-100 cm. Then, for each subsystem we analysed the available information by different soil depths: 0-5, 0-15 and 0-30 cm.In the second step, the soil carbon stock and soil carbon content were analysed considering the combination of various management practices representing business as usual scenario for all sampling depths. The combination of management practices considered are described in Table 2.

**Table 2.** Combinations of the analysed soil management systems.

| |
|---|
| Tillage<br>*OR*<br>tillage and cover crops<br>*OR*<br>tillage and no cover crops<br>*OR*<br>tillage and cover crops and pruning residues<br>*OR*<br>tillage and no cover crops and pruning residues<br>*OR*<br>non tillage and cover crops<br>*OR*<br>non tillage and no cover crops<br>*OR*<br>non tillage and pruning residues and cover crops<br>*OR*<br>non tillage and pruning residues and no cover crops<br>*OR* |

Project MARVIC has received funding from the Horizon Europe
Programme under grant agreement no. 101112942

| |
|---|
| cover crops<br>*OR*<br>cover crops and pruning residues and fertilisers<br>*OR*<br>cover crops and no pruning residues and fertilisers<br>*OR*<br>cover crops mowed<br>*OR*<br>cover crops mowed and pruning<br>*OR*<br>cover crops and herbicides<br>*OR*<br>manure<br>*OR*<br>organic fertilisers |

It is important to note that in this first step, all the existing data were considered in each of the categories using customary classes used in arable crops. For instance, in the NT category, NT (bare soil) or with the presence of cover crops/pruning residues is included under the same analysis. In the second step, the management practices were subdivided into categories that are more in line with the specific situations of woody crops. Therefore, these were subdivided into NT and cover crops, NT and no cover crops, NT and pruning residues and cover crops, NT and pruning residues and no cover crops.

## 2.5. Co-benefits

The different management practices identified in the review have multiple environmental co-benefits, which have been revised in different studies, many of them focusing on olive groves and vineyards (e.g. Montanaro and Gómez, 2024; Gómez, 2017).

Erosion control at the hillslope scale is one of the clearest co-benefits of the use of cover crops (with or without grazing) or mulch or chopped pruning residues, as recognised by multiple studies (Prosdocimi et al., 2016, Gómez et al., 2009). Several experimental and modelling studies (e.g. Bombino et al.; 2021; Bidoccu et al. 2020; Gómez et al., 2017) have determined that the intensity of this reduction is related to the duration of the cover crop, the degree of ground cover achieved and the biomass produced (since it determines the amount of residues to protect the soil surface after the cover crop). Several studies have noted a large variability in these variables in groves and vineyards under cover crop management (e.g. Vicente-Vicente et al., 2017; Guzmán et al., 2019).

The impact of cover crops and mulches in the reduction of runoff, although existing, is smaller than on erosion (Winter et al., 2017; Gómez et al. 2017; Sastre et al., 2016). This can be explained by the different mechanisms controlling both processes (e.g. soil saturation and the presence of a C horizon of low permeability close to the soil surface). This has relevance on the overall impact on improving water balance as compared to bare soil which has shown, on average, no improvement (Winter et al., 2017). Although the use of cover crops provides an increase in infiltration due to runoff reduction, it has an increase in transpiration by the cover crops as compared to bare soil. This is one of the main reasons why cover crops in woody crop systems under Mediterranean conditions are managed as temporary cover crops. In fact, experimental studies in olives and vines (Gómez et al., 2023; Soriano et al. 2018; Gómez, 2017) show a decrease in yield aligned with the predictions of simulation studies (Gómez, 2014).

The integration of livestock into the plots has been described as a successful strategy in areas where there is a tradition of extensive grazing (e.g. sheep grazing in NW Andalusia, see Álvarez et al., (2007)) or there are the conditions for its introduction. It is CF practice that also provides a diversification of farm products and income. The integration of livestock into the farm is a way of managing spontaneous cover crops in some olive groves.

Available studies show a positive effect on overall soil health (understood as the combination of physical, chemical and biological properties) of the CF practices evaluated with the exception of reduced tillage. Several publications note an overall increase in key soil quality indicators like organic carbon content, aggregate stability, nutrient content, and soil respiration, among others (Liebhard et al., 2024; Torrús-Castillo et al., 2022; Winter et al., 2017, Gómez-Muñoz et al., 2016; Gómez et al. 2014, Montanaro et al., 2010; Gomez and Soriano, 2009). This improvement of soil quality is concentrated in approximately 0-10 to 0-20 cm of the soil profile in the lane area, with a large variability among farms with the same CF practices (Liebhard et al., 2024; Guzmán et al., 2019; Vicente-Vicente et al., 2017). The application of organic amendments or organic fertilisation has a positive effect in increasing the levels of organic matter and nutrients in the soil. On a global scale the shift from traditional mineral fertilisation to organic fertilisation is considered one of the practices with a high potential for carbon sequestration (Griscom et al., 2017). In the case of woody crops, available studies noted that the impact (on soil C?) is related to the amount of organic amendments incorporated (Vicente-Vicente et al., 2017). However, its use requires availability of manure or compost at an affordable price, which in many instances is not the case.

CF practices based on the use of cover crops have a positive effect on biodiversity (Martínez-Núñez et al., 2021; Winter et al., 2017, Castro-Caro et al., 2014), which tends to be more intense when the cover crop is composed of a mix of different species (Kratschmer et al., 2019; Gómez et al., 2018), or is mediated by landscape elements and conditions such as hedgerows and presence of specific birds (Castro-Caro et al., 2014) or arthropods (Nordrhein-Westfalen et al., 2019). Due to these complex interactions, the impact of cover crops on increasing the presence of natural enemies for pests is reported in studies (Álvarez et al., 2021), but with a moderate impact in published meta-analysis (Winter et al., 2018). The use of cover crops and/or organic amendments also have a positive effect on soil biodiversity, with its impact mediated by the quality of implementation of the CF practice. Some studies (Landa et al., 2014) indicate a strong effect of the soil type on the impact of the CF practices on the improvement of bacterial communities. Meta-analyses of cover cropping studies show a general positive effect of cover crops on activity and diversity of the soil microbiome as compared with fallow land (Kim et al., 2020; Muhammad et al., 2021).

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

When properly managed, cover crops and mulches also have a positive effect on controlling weeds that are costly or difficult to manage, thereby reducing the need for herbicide application (Henry et al., 2015). The elimination, or reduction of tillage reduces the use of fossil fuels in farm operations, which in turn reduces direct emissions from the farm (Eskandari Damaneh et al., 2022).

## 2.6. Results

Carbon accumulated in aboveground and below-ground biomass

Within the olive groves, only 4 of the 48 selected papers contained information related to above- and below-ground biomass or carbon balance (Annex 1.B). In the paper by Torrús-Castillo et al. (2023), the annual rate of carbon accumulation in the permanent structures of trees ranged between 0.21 to 1.24 t C $ha^{-1}yr^{-1}$, averaging 0.54 t C $ha^{-1}$ $yr^{-1}$. López-Bellido et al. (2017) obtained values similar to the previous ones for the set of 24 olive groves located in Andalusia of different ages, varieties and planting density (0-25 – 1.25 t C $ha^{-1}$).

In the case of olive groves and vineyards, the articles were more specific in terms of the analyses of the above- and below-ground biomass or the carbon balance. Only four, out of twenty-one selected, articles on fruit orchards contained information on the biomass, while in almond trees it as two out of thirteen (Annex 1.B), the other articles that were discarded focus more on life cycle analysis. Liguori et al. (2009) obtained that carbon fixation at tree level in the fruits and in the canopy of orange trees with a traditional plantation framework (494 trees/ha) was two-fold (10.7 kg C $tree^{-1}$, 5.3 t C $ha^{-1}$) compared to that the intensive system (1000 trees/ha); (5.5 kg C $tree^{-1}$, 5.5 t C $ha^{-1}$). Baldi et al. (2018) focused on the effect of fertilisation treatment on plant biomass (kg DW $tree^{-1}$) and yield (kg $tree^{-1}$) at the end of the trial (nectarine orchard). The papers corresponding to the almond trees hardly focused on the biomass of the permanent structures or roots, but rather on that corresponding to the cover crop.

In the case of the vineyards, there were a total of fifteen out of forty-eight articles selected that focused entirely on the carbon accumulated in the above- and below-ground biomass (Annex 1B). Taking into account the set of articles on vineyards, the organic carbon content in the cover crops biomass without considering the root biomass was higher than in the rest of the individual components (1.81 Mg C $ha^{-1}$). This was followed by the leaves (1.47 Mg C $ha^{-1}$) and branches (1.16 Mg C $ha^{-1}$), while the trunk had the lowest carbon content of 0.59 Mg C $ha^{-1}$, although it was roughly 33% of the above-ground biomass of the vine (Figure 1 (A)). The carbon content in 10-15 year old plantations was higher (10.15 Mg C ha-1) than those in older ones of 20-35 years (5.62 Mg C ha-1), while the carbon content was lower in younger plantations (3.08 Mg C ha-1) (Figure 1 (B)).

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

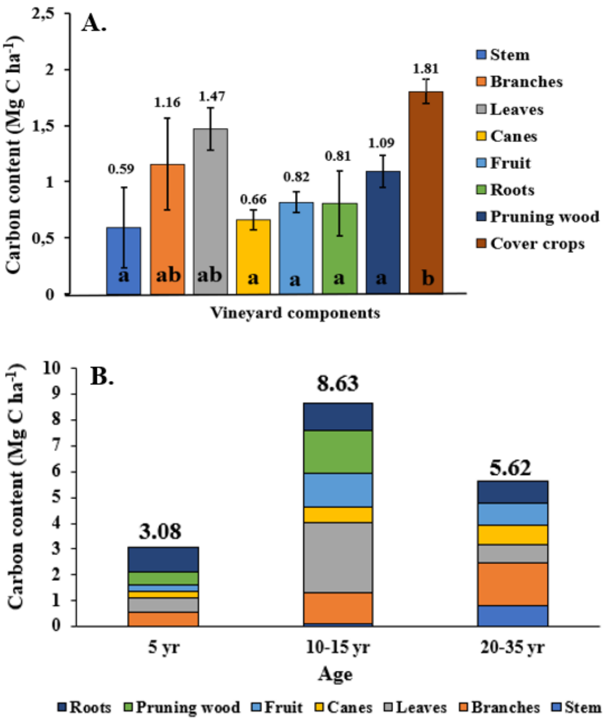



**Figure 1.** Carbon stock in the different components of the vineyards (A) and carbon stock in the different components of the vineyards as a function of the age of the plantation (B). Bars represent standard error. Different letters denote significant differences due to management practices. A confidence level of 95% was considered.

Only a limited number of studies focus on a detailed analysis of the above- and below-ground biomass of permanent structures, especially in relation to below-ground biomass, a very important flow that must be considered to make timely decisions in initiatives such as CF. The limited number of studies also come from different condition such as in the case of the comparison with age, limiting the possibility of extracting quantitative conclusions with acceptable uncertainty. The difficulty of measuring biomass in the field, both above- and below-ground, is understandable due to the cost, time, difficulty and the lack of concise methodologies. However, this lack of consistent regarding methodologies leads to over- or under-estimating the carbon that accumulates in the system. It also represents a barrier to explore strategies that might improve CF practices, like the use of varieties that as a different distribution of biomass in their different components (e.g. roots vs above-ground biomass). Hence, depending on the variety, the above-ground and below-ground biomass could differ and therefore the carbon that accumulates.

Soil carbon content according to management practices

The overall results of soil carbon content did not show significant differences due to the management practices carried out (CC; cover crops, M/OF; manure/organic fertilisers, NT; no tillage and T; tillage) for vineyards, fruit and almond trees. The studies included all sampling depths, although there were articles that sampled up to 100 cm of soil. The average depth in the studies was the first 20 cm of soil. However, in olive groves, the type of management practice led to significant differences ($p < 0.05$) in carbon content. These differences were found between manure/organic fertilisers - tillage and

NT - tillage (Figure 2). It is important to remember that in this case, the NT category does not refer exclusively to bare soil but also includes NT with spontaneous cover. Hence, the management practices were disaggregated as shown in table 5 (NT + no cover crops/ NT + cover crops).

The number of studies considered in the analysis with management practices was lower for fruit trees and almond trees than for olive groves and vineyards. However, for all woody crops the number of articles was even smaller for manure/organic fertilisers management practice. For example, in olive groves the number of articles using manure/organic fertiliser was six out of 61, while this number was 15 out of 119 for different tillage management practices (Figure 2). The reduced number of articles reflects the reality of their implementation by farmers, since the number of farms applying organic amendments is limited due to the economic cost that the application entails, especially for farms that are far from where the organic amendments are produced. This may limit the investment for farmers and make it unprofitable.

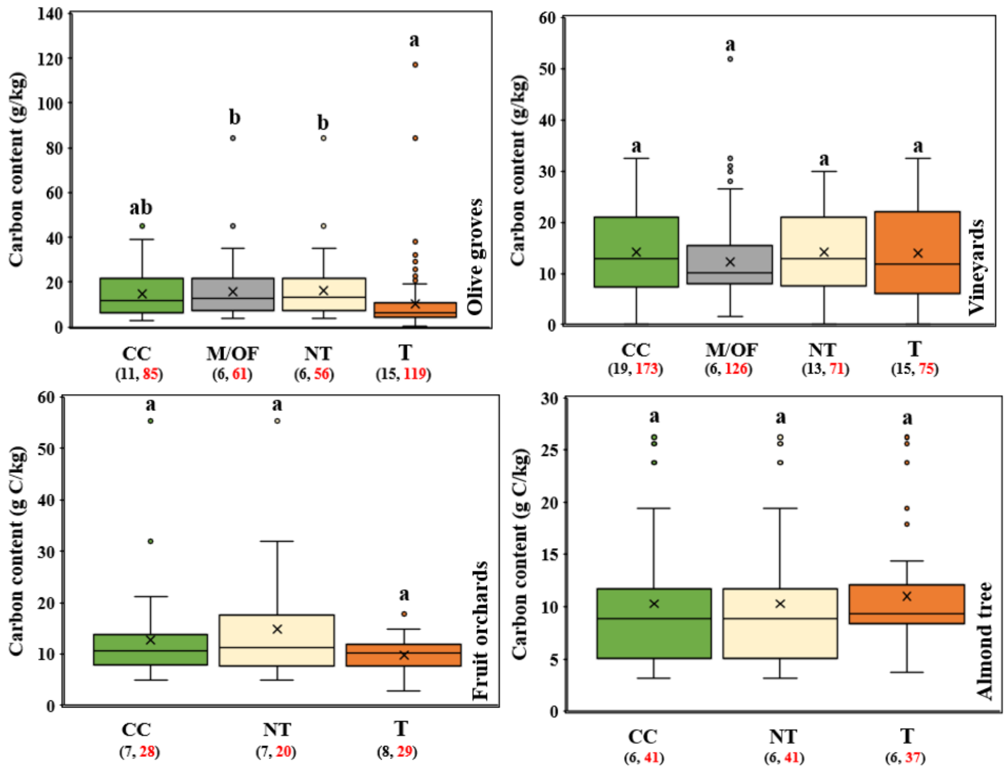



**Figure 2.** Box-plot of carbon content in all sampling depths in different woody crops (olive, vineyards, fruit and almond trees) and management practices (CC: cover crops, M/OF: manure/organic fertilisers, NT: no tillage and T: tillage). The numbers below each management practice indicate the number of articles (in black) and the number of data (in red). The horizontal black line, the x-shaped cross and the borders of the boxes represent the median, the mean and the quartiles respectively. Different letters denote significant differences. A confidence level of 95 % was considered.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

As previously mentioned, there were significant differences in soil carbon content in the case of olive groves between manure/organic fertilisers - tillage and NT - tillage when all sampling depths were considered. We need to clarify that we used no-tillage as a class because it is commonly used in other studies on soil management in agricultural systems although in the case of olives requires further clarification (e.g. Gómez et al., 2014), as it will be discussed below (NT in this case does not refer exclusively to bare soil). SOC content in olive groves was higher with NT (16.2 g/kg) compared to tillage (10.3 g/kg). Following the NT practice, the application of organic amendments and the implementation of cover crops resulted in soil carbon content of 15.7 g/kg and 14.9 g/kg, respectively. In the case of fruit orchards, as in the olive grove, NT resulted in higher soil carbon content of 14.8 g/kg and 16.2 g/kg, respectively, while tillage showed the lowest (9.8 g/kg and 10.3 g/kg, respectively). In the case of almond trees and vineyards, cover crops showed a higher SOC content compared to the rest of the practices, despite showing no significant differences (Table 3).

**Table 3.** SOC content (g/kg) under different management practices and sampling depths. Management practices with higher soil carbon content values are shown in green, while the opposite situation is shown in red. Different letters denote significant differences. A confidence level of 95 % was considered.

| System | Cover crops | Manure/Organic Fertilisers | No tillage | Tillage |
|---|---|---|---|---|
| **Olive groves** | 14.90 ± 1.10 ab | 15.72 ± 1.67 b | 16.19 ± 1.79 b | 10.32 ± 1.28 a |
| **Fruit orchards** | 12.77 ± 1.57 a | | 14.81 ± 2.57 a | 9.76 ± 0.60 a |
| **Almond orchards** | 17.86 ± 4.28 a | | 16.36 ± 5.98 a | 16.64 ± 4.45 a |
| **Vineyards** | 14.26 ± 0.60 a | 12.35 ± 0.64 a | 14.11 ± 0.96 a | 13.87 ± 0.97 a |
| | | | | |
| **Average ± SE** | 14.95 ± 1.07 a | 14.04 ± 1.19 a | 15.36 ± 0.54 a | 12.65 ± 1.61 a |

There were no significant differences in SOC content because of the management practices (CC: cover crops, M/OF: manure/organic fertilisers, NT: no tillage – this category does not refer exclusively to bare soil and T: tillage) and soil profile depth (0-5, 0-15 and 0-30 cm) for olive, almond and fruit crops but there were differences in the case of vineyards (Table 4). These differences were observed at a depth of 0-30 cm, with higher values of SOC content under tillage (32.4 g/kg), followed by NT (26.9 g/kg) and cover crops (26.5 g/kg). The trend observed was more organic carbon content in the soil under cover crops and NT in the first 5 cm of soil. Nevertheless, it is important to highlight that there was a small number of articles that reported soil carbon content at 0-5 cm depth. Most studies presented data on 0-15 cm and 0-30 cm depths. As shown in Table 4, the number of articles available for the 0-5 cm range was limited, while most articles focused on the 0-15 cm range. In the same table, the systems are analysed independently, but within them. For example, in olive groves, all practices and depths are analysed together. Therefore, there are no significant differences in cover crops for the different depths considered, nor with the rest of the management practices at a depth of 0-5 cm.

**Table 4.** SOC content (g/kg) under different management practices and sampling depths (0-5, 0-15 and 0-30 cm). Different letters denote significant differences (a confidence level of 95 %

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

was considered). The numbers in parentheses indicate the number of articles selected and in red the number of data used in the analysis.

| System | Depth (cm) | Cover crops | Manure/Organic Fertilisers | No tillage | Tillage |
|---|---|---|---|---|---|
| OLIVE GROVES | 0-5 | 26.33 ± 3.30 a (2, 14) | | 23.99 ± 2.72 a (2, 18) | 12.01± 3.71 a (3, 4) |
| | 0-15 | 35.11 ± 3.71 a (5, 22) | 51.30 ± 32.8 a (1, 2) | 35.45 ± 3.46 a (4, 23) | 21.50 ± 5.20 a (5, 21) |
| | 0-30 | 11.86 ± 1.90 a (1, 7) | 12.90 ± 3.48 a (1, 4) | 24.38 ± 7.22 a (2, 7) | 13.25 ± 6.01 a (6, 7) |
| FRUIT ORCHARDS | 0-5 | 18.95 ± 4.47 a (1, 4) | | 18.98 ± 3.47 (2, 5) | 17.90 ± 6.86 a (2, 3) |
| | 0-15 | 9.40 ± 1.70 a (2, 6) | | 25.45 ± 7.65 a (2, 2) | 17.02 ± 6.62 a (3, 8) |
| | 0-30 | 17.06 ± 2.31 a (4, 8) | | 13.47 ± 5.1 a (3, 4) | 15.68 ± 2.40 a (4, 8) |
| ALMONDS ORCHARDS | 0-5 | 12.68 ± 1.08 a (1, 3) | 14.40 a (1, 1) | 10.70 a (1, 1) | 13.67 ± 0.74 a (1, 2) |
| | 0-15 | 11.37 ± 3.01 a (2, 9) | | 5.50 ± 1.14 a (2, 5) | 14.54 ± 3.51 a (2, 7) |
| | 0-30 | 7.85 ± 0.33 a (1, 4) | | 7.85 ± 0.33 a (1, 4) | 8.50 ± 0.2 a (1, 2) |
| VINEYARDS | 0-5 | 18.82 ± 4.11 ab (3, 11) | 22.90 ab (1, 1) | 19.32 ± 8.61 ab (3, 5) | 15.44 ± 3.06 ab (3, 9) |
| | 0-15 | 23.21 ± 1.82 ab (7, 34) | | 23.70 ± 3.51 ab (5, 16) | 17.43 ± 2.34 ab (6, 20) |
| | 0-30 | 26.55 ± 1.84 b (10, 66) | 10.71 ± 0.91 a (3, 12) | 26.86 ± 3.51 b (6, 25) | 32.41± 4.47 b (6, 17) |

Table 5 disaggregates the combinations of management practices considering all sampling depths for which our review found data, indicating some differences. In this case, a distinction is made between non-tillage with spontaneous cover crops (NT + cover crops) and bare soil without cover crops (NT+ no cover crops). In olive groves, the combination of NT + application of pruning residues + cover crops presented the highest values of organic carbon content in the soil (21.57 g/kg), as was noted for fruit trees (19.03 g/kg). However, the lowest levels were obtained under NT with the absence of cover crops for the olive grove, known as bare soil (5.91 g/kg). In fruit trees, the lowest levels were obtained when there was no cover crop in the soil, despite NT and application of pruning residues (7.55 g/kg). In almond trees, the opposite trend to olive and fruit trees occurred, since the organic carbon content in the soil is lower when NT, pruning residues and plant cover are combined. In vineyards, it should be noted that the organic carbon content in the soil was higher when the soil was tilled, no cover crop is present, and pruning residues are added (20.10 g/kg). The lowest values are observed when herbicides are applied to the cover crops (6.67 g/kg).

Overall, for all woody crops analysed, the implementation of cover crops, pruning residues and the application of organic amendments (manure/organic fertilisers) resulted in the highest content of organic carbon in the soil, averaging 16.13 g/kg. The elimination of cover crops using herbicides resulted in the lowest values of organic carbon in the soil, with an average of 6.52 g/kg. However, considering all the possible combinations of management practices for each of the woody crops regardless of whether they are more or less sustainable, resulted in olive groves having an enhanced organic carbon in the soil, followed by vineyards, with similar values for fruit and almond trees, but without significant differences ($p = 0.61$) (Table 5).

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

**Table 5.** SOC content (g/kg) under different management practices and through the soil profile. For each woody crop, the management practice that has the highest soil carbon content (green) and the lowest (red) are indicated. The average value of SOC for the set of woody crops and a given practice is indicated (beige), and the average value of organic carbon considering the set of practices for each woody crop is indicated (blue). Different letters denote significant differences. A confidence level of 95 % was considered.

| Management practices | Olive groves | Fruit orchards | Almond orchards | Vineyards | Average |
|---|---|---|---|---|---|
| **Tillage + cover crops** | 9.68 ± 1.57 | 10.50 ± 0.72 | | 17.13 ± 1.32 | 12.44 ± 2.04 |
| **Tillage + no cover crops** | 10.15 ± 1.53 | 8.14 ± 1.08 | 11.00 ±1.02 | 9.12 ± 1.81 | 9.60 ± 0.62 |
| **Tillage + cover crops + pruning residues** | 14.80 ± 5.02 | 9.72 ± 0.53 | | 15.15 ± 3.22 | 13.22 ± 1.52 |
| **Tillage + no cover crops + pruning residues** | 9.15 ± 2.19 | | | 20.10 ± 4.5 | 14.62 ± 3.87 |
| **No tillage + cover crops** | 17.18 ± 1.36 | 15.03 ± 2.99 | 10.28 ± 0.98 | 14.35 ± 1.01 | 14.21 ± 1.44 |
| **No tillage + no cover crops** | 5.91 ± 0.95 | 7.55 | | | 6.73 ± 0.58 |
| **No tillage + pruning residues + cover crops** | 21.57 ± 3.49 | 19.03 ± 7.36 | 9.30 ± 0.49 | 8.15 ± 1.34 | 14.51 ± 3.39 |
| **No tillage + pruning residues + no cover crops** | | 7.55 | | | 7.55 |
| **Cover crops + pruning residues + fertilisers** | 19.91 ± 2.25 | | 12.36 ± 0.75 | | 16.13 ± 2.67 |
| **Cover crops + no pruning residues + fertilisers** | | | | | |
| **Cover crops mowed** | 15.63 ± 1.50 | 13.08 ± 1.98 | 13.25 ± 1.39 | 15.79 ± 1.23 | 14.44 ± 0.74 |
| **Cover crops mowed + pruning** | 21.57 ± 3.49 | 12.38 ± 2.21 | 13.25 ± 1.39 | 9.65 ± 1.42 | 14.21 ± 2.57 |
| **Cover crops + herbicides** | 6.37 ± 1.30 | | | 6.67 ± 0.48 | 6.52 ± 0.11 |
| | | | | | |
| **Average ± SE** | 13.81 ± 1.76 a | 11.44 ± 1.29 a | 11.57 ± 0.67 a | 12.90 ± 1.54 a | |

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Carbon stocks of the management practices

Carbon stock (Mg C ha$^{-1}$) did not show significant differences among the different management practices carried out (CC: cover crops, M/OF: manure/organic fertilisers, NT: no tillage and T: tillage) when considering all sampling depths (although there were articles that sampled up to 100 cm of soil, the average depth of the studies was the first 20 cm of soil) for vineyards, fruit trees and almond trees. However, in olive groves the type of management practice led to significant differences ($p = 0.01$) in carbon stocks between CC- M/OF and M/OF- NT (Figure 3).

The number of studies and carbon stock data considered in the analysis with management practices as a variable was lower for fruit and almond trees, compared with olive groves and vineyards, which had a higher number. However, the number of articles was reduced further when the data was filtered for manure/organic fertilisers management practice. In fact, no articles were found for fruit and almond trees with information relating to manure/organic fertilisers as a management practice (Figure 3).

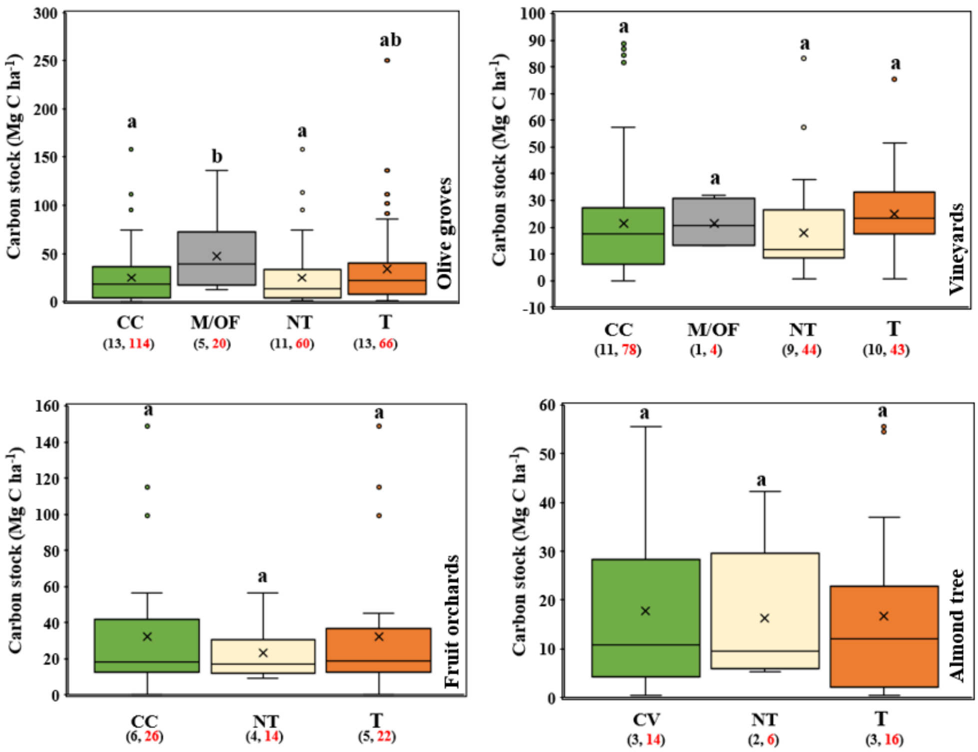



**Figure 3.** Box-plot of carbon stock considering all sampling depths in different woody crops (olive, vineyards, fruit and almond trees) and management practices (CC: cover crops, M/OF: manure/organic fertilisers, NT: no tillage and T: tillage). The numbers below each management practice indicate the number of articles (in black) and the number of carbon stock data (in red). The horizontal black line, the x-shaped cross and the borders of the boxes represent the median, the mean and the quartiles. Different letters denote significant differences. A confidence level of 95 % was considered.

There were significant differences ($p < 0.05$) in carbon stocks in the case of olive groves between CC- M/OF and M/OF- NT when all sampling depths were considered. For olive groves the carbon stocks were higher with the application of manure/organic

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

fertilisers (47.6 Mg C ha$^{-1}$) and lower when NT (24.9 Mg C ha$^{-1}$) was applied. For all woody crops, the carbon stocks were lower under NT (does not refer exclusively to bare soil). In the case of almond trees, the highest SOC stocks were observed when cover crops were applied (17.9 Mg C ha$^{-1}$). For fruit trees and vineyards tillage shows the highest SOC stocks of 33.7 and 27.3 Mg C ha$^{-1}$, respectively (Table 6). Despite the absence of significant differences (p = 0.332) when averaging the SOC stocks among all systems for each management practice, the carbon stock in the soil is higher under manure application (34.5 Mg C ha$^{-1}$), followed by tillage (27.3 Mg C ha$^{-1}$) and cover crops (24.3 Mg C ha$^{-1}$), while NT presents the lowest carbon stock in the soil (20.5 Mg C ha$^{-1}$).

**Table 6.** Carbon stock (Mg C ha$^{-1}$) under different management practices and sampling depths. Management practices with higher soil carbon content values are shown in green, while the opposite situation is shown in red. Different letters denote significant differences (a confidence level of 95 % was considered).

| System | Cover crops | Manure/Organic Fertilisers | No tillage | Tillage |
|---|---|---|---|---|
| **Olive groves** | 24.89 ± 2.50 a | 47.60 ± 7.51 b | 24.88 ± 3.91 a | 34.24 ± 5.01 ab |
| **Fruit orchards** | 33.21 ± 6.32 a | | 23.17 ± 4.37 a | 33.66 ± 7.10 a |
| **Almond orchards** | 17.86 ± 4.28 a | | 16.36 ± 5.98 a | 16.64 ± 4.44 a |
| **Vineyards** | 21.34 ± 2.09 a | 21.50 ± 4.73 a | 17.77 ± 1.94 a | 24.83 ± 2.34 a |
| | | | | |
| **Average ± SE** | 24.33 ± 3.29 a | 34.55 ± 9.23 a | 20.55 ± 2.06 a | 27.34 ± 4.17 a |

When considering the effect of different management practices on various crops, considering the different sampling depths, there were no significant differences in soil carbon stock for vineyards. However, significant differences were observed in the case of olive groves (Table 7). Due to the limited number of articles, the difficulty in grouping the information by sampling depth, and the multiplicity of management practices, it was not possible to reliably conduct the analyses for fruit and almond trees. In the systems with olive groves, it was found that the cover crops influence the carbon stock depending on the sampling depth (0-5 and 0-30 cm). The trend was higher carbon stock in the first 5 cm of soil under the implementation of cover crops and NT when organic amendments were not applied and lower values when the soil was tilled.

In the Table 7, the systems are analysed independently, but within them. For example, in olive groves, all practices and depths are analysed together. Therefore, when cover crops is analysed, significant differences in carbon stock are observed at 0-5 cm and 0-30 cm, but none are observed between 0-5 cm and 0-15 cm. At a depth of 0-15 cm, there are no significant differences in carbon stock depending on the management practice carried out.

If we analyse all the possible combinations of management practices carried out, considering all the different sampling depths, we can see that for each woody crop the soil carbon stock varies depending on the practice (Table 8). In olive groves, the combination of "tillage, no cover crops and pruning residues" presented the highest values of carbon stock in the soil. However, it cannot be considered representative since the value of 105.8 Mg C ha$^{-1}$ corresponds to only one article from a sampling depth of 0-

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

100 cm (Fernández-Romero et al., 2014). Therefore, it is more representative to consider the combination of “NT, pruning residues and cover crops” as the practice that implies the highest carbon stock in the soil (59.0 Mg C $ha^{-1}$), since it considered more articles at different sampling depths (5 articles, 14 data). The lowest levels of C stock were obtained under “NT, pruning residues and no cover crops” (8.9 Mg C $ha^{-1}$) (Table 8). In vineyards, removing cover crops by mowing and leaving the residues on the ground, followed by applying pruning residues, resulted in the highest carbon stock in the soil (24 Mg C $ha^{-1}$) compared to when pruning residues were not applied (15.2 Mg C $ha^{-1}$).

**Table 7.** Carbon stock (Mg C $ha^{-1}$) under different management practices and sampling depths (0-5, 0-15 and 0-30 cm). Different letters denote significant differences. The numbers in parentheses indicate the number of articles selected and in red the number of data used in the analysis.

| System | Depth (cm) | Cover crops | Manure/Organic Fertilisers | No tillage | Tillage |
|---|---|---|---|---|---|
| OLIVE GROVES | 0-5 | 9.05 ± 0.49 a (2, 10) | | 9.73 ± 1.87 ab (1, 3) | 8.35 ab (1, 1) |
| | 0-15 | 17.86 ± 1.28 ab (2, 10) | 17.53 ± 0.73 ab (1, 4) | 14.69 ± 6.99 ab (3, 8) | 14.21 ± 2.55 ab (4, 9) |
| | 0-30 | 37.62 ± 4.39 b (7, 39) | 51.00 ± 7.31 ab (1, 4) | 38.81 ± 7.11 b (6, 23) | 28.60 ± 2.49 ab (7, 25) |
| VINEYARDS | 0-5 | 9.85 ± 0.36 a (1, 2) | | 9.85 ± 0.36 a (1, 2) | 4.12 a (1, 1) |
| | 0-15 | 16.63 ± 3.08 a (4, 22) | | 18.20 ± 3.73 a (2, 10) | 38.90 ± 0.94 a (2, 5) |
| | 0-30 | 35.90 ± 5.89 a (6, 35) | 21.50 ± 4.73 a (2, 4) | 25.43 ± 5.33 a (4, 12) | 39.87 ± 16.73 a (3, 4) |

The combination of “tillage, no cover crops and pruning residues resulted in the highest carbon stock in the soil. However, due to the lack of representativeness, it can be said that the combination of “no –tillage, pruning residues and cover crops” presented the highest values, averaging 37.8 Mg C $ha^{-1}$ for vineyards and olive groves. The lowest values were obtained when a combination of NT without cover crops (using herbicides or in degraded soils without vegetation growth) were used. The combination of “NT, pruning residues and no cover crops” averaged 8.9 Mg C $ha^{-1}$ for the set of woody crops studied. Considering all the possible combinations of management practices for each of the woody crops resulted in olive groves having a higher reported carbon stock in the soil compared with vineyards ($p = 0.031$) (Table 8).

<u>Summary of co-benefits of mitigation practices by agricultural systems</u>

Table 9 shows the main drivers affecting variability, adaptation, benefits, trade-offs effect on productivity and reference of the main management practices for woody crops.

As can be seen in table 9, the management practices selected present more benefits than drawbacks. Obviously, depending on the farm and its location, these practices may be more or less suitable. However, in the Mediterranean countries, it has been shown that these management practices can be implemented on the farm without too much complexity. However, of all the practices shown in the table, the least frequent is the use of organic amendments due to the economic cost that this would entail for the farmer.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

**Table 8.** Carbon stock (Mg C ha$^{-1}$) under different management practices and sampling depths. For each woody crop, the management practice that has the highest soil carbon content (green) and the lowest (red) are indicated. The average value of SOC for the set of woody crops and a given practice is indicated (beige), and the average value of organic carbon considering the set of practices for each woody crop is indicated (blue). Different letters denote significant differences. A confidence level of 95 % was considered.

| Management practices | Olive groves | Vineyards | Average |
|---|---|---|---|
| **Tillage + cover crops** | 26,59 ± 4.92 | 23,48 ± 1.58 | 25,04 ± 1.56 |
| **Tillage + no cover crops** | 33,25 ± 7.34 | 18,39 ± 6.07 | 25,82 ± 7.43 |
| **Tillage + cover crops + pruning residues** | 32,62 ± 19.81 | 22,18 ± 1.12 | 27,40 ± 5.21 |
| **Tillage + no cover crops + pruning residues** | 105,80 | | 105,80 |
| **No tillage + cover crops** | 29,02 ± 5.12 | 16,49 ± 1.97 | 22,76 ± 6.27 |
| **No tillage + no cover crops** | 13,50 ± 2.53 | | 13,50 |
| **No tillage + pruning residues + cover crops** | 59,01 ± 10.91 | 16,63 ± 2.14 | 37,82 ± 21.19 |
| **No tillage + pruning residues + no cover crops** | 8,95 ± 1.31 | | 8,95 |
| **Cover crops + pruning residues + fertilisers** | 32,04 ± 3.61 | | 32,04 |
| **Cover crops + no pruning residues + fertilisers** | 36,00 ± 9 | | 36,00 |
| **Cover crops mowed** | 29,49 ± 2.28 | 15,24 ± 1.33 | 22,36 ± 7.13 |
| **Cover crops mowed + pruning** | 30,87 ± 3.07 | 24,00 ± 1.78 | 27,44 ± 3.43 |
| **Cover crops + herbicides** | 36,73 ± 15.41 | | 36,73 |
| | | | |
| **Average** ± SE | 36,20 ± 5.46 a | 20,16 ± 1.01 b | |

Project MARVIC has received funding from the Horizon Europe
Programme under grant agreement no. 101112942

**Table 9.** Drivers affecting variability, adaptation, benefits, trade-offs effect on productivity and reference of the main management practices of woody crops.

| | Drivers affecting variability | Adaptation | Benefits | Trade-offs | Effect on productivity | Reference |
|---|---|---|---|---|---|---|
| **Cover crops** | Climate, soil texture, crop type, model for implementing cover crops on the farm (in the streets, under the canopy or covering the entire soil), rabbit density, livestock, fertilisation, amonth others. | Improved soil structure, water infiltration and water holding capacity, pest resilience, reduce the erosion and trapping nutrients. | It favours ant communities or as pest control, reduce soil erosion, in addition to promoting water infiltration and availability, entry of carbon into the soil and the retention of nutrients | Without the addition of organic amendments or pruning residues to the soil, the carbon content in the soil would decrease over time. Poor management of the cover crops can lead to limited water for the main crop. | In some cases, cover crops may reduce available soil water and thus negatively affect yields. | Álvarez et al., 2007; 2021; Biddoccu et al., 2020; Castro-Caro et al., 2014; Gómez 2017, 2014, 2017, 2018, 2023; Kratschmer et al., 2019; Landa et al., 2014; Liebhard et al., 2024; Martínez-Núñez et al., 2021; Sastre et al., 2016; Soriano et al., 2009, 2018; Torrús-Castillo et al., 2022; Winter et al:, 2018 |
| **No-tillage** | Climate, soil texture, crop type, duration since tillage abandonment, pruning/cover crops residues and fertilisation. | Higher resilience against weather extremes due to soil erosion reduction and soil water capacity increase | By reducing soil erosion and compaction, NT helps maintain soil structure and nutrients, increases organic matter, reduces GHG emissions due to lower fuel use, can retain more water, and promotes soil biodiversity | Reduces the amount of water that infiltrates and increases the problems associated with waterloggingn, mainly in areas with steep slopes. The use of herbicides to eliminate cover crops leads to water pollution. Therefore, no- tillage can have an unfavorable effect due to an increase in water content and hydromorphism with the consequent emission of GHG. On the other hand, there are studies showing | Positive, may be associated with difficult weed control | Dao, 1996; Gómez et al., 2005 |

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | that in an olive grove with an average slope of 13.4 %, soil losses without tillage were more than twice as high as with tillage. | | |
| **Reduced tillage** | Climatic, Soil texture crop types, frequency, pruning/cover crops residues and fertilisation. | It reduces erosion and loss of water from the soil, and indirectly reduces $CO_2$ emissions. | Reduce fossil fuel use and increase soil water retention. | Some increase in pesticide use. The breakdown of soil aggregates leads to a decrease in SOC and an increase in $CO_2$ emissions. This short-term increase in $CO_2$ emissions is due to a physical process, generating a release of this gas stored in the porous structure of the soil. | Positive, may be associated with difficult weed control | Reicosky and Lindstrom, 1993; Álvaro-Fuentes et al., 2007 |
| **Organic amendments and pruning residues** | Residue quality, health of the previous crop, proximity to the material to be added to the soil and its transport cost, frequency with which the pruning residues are applied and soil type. | Increase soil fertility, soil moisture retention, and reduce soil erosion. | They increase the levels of organic matter, nutrients and even increase the oil content in the fruit ten years after application, and from the point of view of GHG emissions, the change from traditional chemical fertilisation to organic fertilisation is considered one of the practices with the highest benefit/cost ratio. It reduces water loss through evaporation and decreases temperature fluctuations in the soil. On the other hand, | Promote N mineralisation and potentially enhancing $N_2O$ and $CH_4$ emissions. Conflicting goals - retention of crop residues for increasing SOC versus using residues for energy production must be considered. Additional energy costs required for chopping and incorporating residues or the cost to transport the organic amendments. | Positive | Bombino et al., 2021; Fernández Hernández et al., 2015; Llorca et al., 2004; Repullo et al., 2012 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | pruning remains act as a soil protector in case of intense rain, it also protects against erosion, and in case of heat and frost it has an insulating effect. In addition, the soil structure is continuously improved, and as microorganisms slowly disintegrate these residues, numerous nutrients are provided. | | | |
| **Livestock** | Climatic condition, SOC content, soil texture, crop and farm types, residue management and fertilisation | Increase soil fertility, soil moisture retention, and reduce soil erosion. | The presence of livestock serves as an effective control of cover crops, thereby reducing the use of machinery (reduction in fuel use), favoring the diversification of cover crops species, in addition to providing an extra contribution of organic fertilisation without the need for external inputs. | Soil compaction, potencially enhancing N2O and CH4 emissions. | Positive | Álvarez et al., 2007; Torres et al., 2016 |

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

## 2.7. Discussion

Most of the studies include the sowing of cover crops, which is usually carried out in autumn (except for some study cases that report spring sowing), which offers optimal conditions for plant establishment. The following cover crop species stand out: *Fescue*, *Clover*, *Triticale*, *Brachypodium*, *Ryegrass*, *Oats*, *Vetch*, *Barley*, *Vicia villosa*, *Medicago* and a mixture of different species. Most of the studies managed the cover crops as a temporary cover crop, meaning their growth is limited using chemical (herbicides) or mechanical (weeder) methods at some point in late winter or early spring (February March). Sometimes, particularly in the case of mechanical control, a second application or weeder pass is carried out in mid-spring (April-May) if cover crop growth is still high. Tillage management in the reviewed studies is carried out, in most cases, three times a year at a depth of approximately 15-20 cm. Usually, the first pass consists of deeper tillage using a mouldboard plough or disc plough, while the second and third passes are more superficial using a cultivator, spike harrow or roller. There is some variability among studies, with some studies using a reduced, and shallower number of tillage passes, e.g. two cultivator passes a year.

It is important to note that the number of articles is reduced when the sampling depth is 0-5 cm, while there is a larger number of articles that present data for 0-30 cm soil depth, which can make decision-making difficult due to the limited information at other sampling depths. Despite the difficulty of taking soil samples in the field at different depths or throughout the entire soil profile, it is necessary to conduct studies that include the greatest number of possible soil depths to better understand the influence of soil depth on the distribution or content of carbon. The fact that the studies always focused on the same sampling depths made it difficult to clearly understand the real impact of these management practices on organic carbon content, and thus on CF.

Another problem is that articles usually provide information on carbon content in percentage or grams per kilo, but not on carbon stock, so in many cases it must be calculated from the bulk density, which is sometimes not provided in the articles, or if information is provided, it is not made clear whether the coarse fragments were removed or not, which could lead to over- or under-estimating the results. In other cases, it is not specified whether the samples were taken in the alley or under the canopy, so it was assumed that in most cases the soil samples were taken in the alley if no further information was provided. Therefore, due to these types of aspects, it should be proceeded with caution, since taking samples under or outside the canopy would influence the organic carbon content, and consequently, the carbon stock of the soil.

Based on the individual analysis of the different articles and their subsequent processing, it can be concluded that while there is a significant number of studies focusing on SOC, they are insufficient to provide quantitative information for a reliable appraisal of the different CF practices with moderate uncertainty. Part of this can be explained by a myriad of possible combinations of management practices that can be implemented on a given farm (see Table 2), combined with the lack of consistency in the soil depth explored in different studies. Also, there are large differences in SOC between the lane and the under-canopy area. Despite it being a typical feature in woody crops like olives know (Gómez et al., 1999, 2014), this difference is not widely studied (Gómez et al., 2022, 2024). The large variability in edaphoclimatic and agronomic conditions, which determine differences in biomass productivity of different farms, further increases the variability even under relatively homogeneous conditions (Gómez et al., 2022; 2023). Drawing reliable conclusions is therefore difficult. For an appropriate appraisal of CF practices, it is necessary to take samples that cover deeper soil depths to determine the distribution of carbon in the soil profile according to the management practice implemented. In general, the reviewed articles provided a limited explanation of the specific details of the management practices that were realised. For example, it is often unclear how long a management practice was implemented for, the different combination of practices that were carried out on the farm, or the irrigation dose applied, among others. Also, the bulk density values are not always provided in the articles, and when they are, it is not clear whether the coarse fragments are taken into account.

Our review highlights the need for establishing clear guidelines on good practices in experimental studies on SOC, some of which can be easily implemented. These are, for example:

**i)** listing the coarse fragment content and bulk density;
**ii)** a detailed explanation of the management and agronomic practices, the age of the plantation and the number of years those practices have been implemented;
**iii)** sampling of all the relevant soil depths, rather than to the maximum rooting depth or a standard depth, which might be in the range of 0.8-1.0 m;
**iv)** sampling soil in two different areas, below canopy and in the lane area, the latter being the area where most of the CF practices are implemented; and
**v)** determining the baseline in soil in all the plots at the start of the experiment, instead of assuming an initial equal value. Another option, it would be the establishment of a control plot where conventional BAU practices are applied.

These guidelines will help generate reliable experimental data that could assist in discriminating the effect of other factors, such as climate and soil type, on management practices. It will also help close the carbon cycle of the system and improve its carbon footprint, hence allowing for a better understanding of the effect of specific CF practices in relation to carbon accumulation in above- and belowground biomass of woody crops.

Despite the uncertainties and gaps in knowledge, it can be confirmed that it is essential to consider the role of cover crops, the permanent structures of woody crops and some management practices in carbon dynamics. The results show that the amount of organic carbon in cover crop contains a relevant (significant?) share of the carbon in the systems, e.g. C in vineyards was higher than in any of the independent components of the vine biomass (but not as a whole).

For management practices, the trend was towards a higher organic carbon content and carbon stocks in the soil with no –tillage, combined with cover crops and the application of organic amendments compared to tillage in all woody crops at all depths. However, in most cases there were no results on the role of the application of organic amendments on soil carbon, since the number of existing studies is limited. This indicates the importance of this subject for researchers in the field, who are aware of the difficulty farmers face when it comes to applying organic amendments on their farms. Some of the obstacles include the availability of organic materials, the associated costs to buy these, and the costs involved in transporting the material to their farms.

Given the uneven distribution of studies, and the large variability, the experimental information on the effect of possible combinations of management practices on the organic carbon changes gave different results for different woody crops. This is counterintuitive, since the studies come from analogous conditions, and they are regulated by the same physical, chemical and biological processes. This is, again, a call for the need for a more standardised way to carry out studies on SOC in woody crops to generate experimental information that could be integrated in the future in a joint meta-study.

The general trend was higher carbon levels under NT with application of pruning residues and use of cover crops, and the lowest values when there was no cover crop or it was removed with herbicides or pruning residues were not added ("NT and no cover crops" OR "NT and pruning residues and no cover crops" OR "cover crops and herbicides. The olive grove was the woody crop that presented the highest carbon stock in the soil. This could be due to the fact that in olive groves there is a greater diversity of practices compared to other woody crops.

## 2.8. Insights

### *2.8.1. Scientists:*

- There is the need to improve the quality of publications on SOC, particularly in woody crops, standardizing several definitions? to prevent sources of confusion and reduce variability. The use of different units, lack of key variables (e.g. bulk density) or detail in the explanation of the management practices carried out in the study and not specifying the time that these management practices have been implemented make it difficult to actually interpretate the results

- Reduced experimentation period, single-year studies which does not capture the dynamic evolution of the systems in biomass or in the soil.

- The variability of factors such as climate and soil type masks the role of management practices in the carbon content and carbon stock of the soil.

- The variability of the systems in terms of management practices makes it difficult to compare these in relation to the carbon stock in the soil.

- The depth and location where soil samples are taken may influence the final result.

- More studies and methodologies are needed focused on analysing the carbon that accumulates in the tree, especially in the roots.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

- Not knowing clearly what the baseline value of carbon content in the soil before applying management practices makes it impossible to know the mitigation potential (t C $ha^{-1}$ $yr^{-1}$).

- It is impossible to calculate the carbon stock if bulk density data is not provided. Not excluding coarse fragments in determining the bulk density leads to errors in calculating the soil carbon stock.

- Not indicating the irrigation dose does not allow knowing the possible relationship between the increase in biomass production and organic carbon.

- Not specifying the planting frame or the age of the trees in the studies makes it difficult to make assumptions about the mitigation potential (t C $ha^{-1}$ $yr^{-1}$).

### 2.8.2. *End-users/Stakeholders:*

- The carbon that accumulates in the permanent structures of woody crops will depend on the age of the plantation and the type of pruning.

- The model of implementation of the cover crops, that is, whether it covers the entire soil, is in strips or under the canopy of the trees, and the species, will influence the organic carbon in the soil.

- Cover crops play an essential role in SOC, as do permanent tree structures and roots.

- As for management practices, the trend was towards a higher content of organic carbon and carbon stock in the soil with no-tillage combined with cover crop and the application of organic amendments and towards lower in systems with tillage and bare soil in all crops and depths.

- The application of organic amendments increases the carbon content in the soil compared to other practices. Therefore, options must be able to apply them in the field if transport costs allow it.

- The best combination of management practices that results in a higher content of organic carbon in the soil and carbon stock was “no-tillage and the application of pruning residues and the existence of cover crops” while the lowest values where when there was no cover crop (by herbicide or mechanical methods) or pruning residues were not added.

- The olive grove was the woody crop system that has the highest reported carbon stock in the soil.

### *2.8.3. Policy makers:*

- Sustainable management practices like cover crops (under different strategies) and the use of pruning residues increase organic carbon in the soil, albeit available literature presents a large variability in the quantification of this increase.

- Literatures on the organic carbon content or carbon stock in the soil present different results for different woody crops. This might a result of the large variability among studies, the methodological differences and the reduced number of studies.

- The carbon footprint must take into account the carbon balance of the woody crop and the emissions produced by the different agricultural practices. Carbon balance is understood as all the carbon inputs and outputs that occur in the system, that is, the carbon that accumulates in the tree as well as in the soil, including soil respiration, decomposition of materials added to the soil or erosion.

# 3. Peatlands

*Jens Leifeld[1] and Milagros Torrús Castillo[2]*

*[1] Agroscope, Switzerland*

*[2] Spanish National Research Council (CSIC), Spain*

## 3.1. Methodology for information search.

The analysis is mostly based on review studies on GHG emissions from drained and rewetted peatlands in Europe (Aben et al., 2024; Bianchi et al., 2021; Evans et al., 2021; Koch et al., 2023; Tiemeyer et al., 2020), plus two studies from individual sites that were not included (Paul et al., 2021; Paul et al., 2024). Study sites were from Germany, Denmark, the Netherlands, UK, Switzerland, and Ireland. Site data that were mentioned more than once (e.g. used in two different review studies) were counted only once. Gases considered are $CO_2$ and $CH_4$. $N_2O$ data from the review of European measurements by Lin et al., (2022) were analysed but not considered, as the relationship to a change in water table (WT) depth, e.g. rewetting, is less uniform.

In all studies, the $CO_2$ balance refers to the net ecosystem productivity (NEP), which takes into account the $CO_2$ balance measured in the field and the carbon in harvested export from the field. Studies that did not report NEP or did not measure for at least one full year were not included. Information on mean groundwater depth was considered mandatory. In total, 258 full-year measurements for $CH_4$ and 240 full-year measurements for $CO_2$ were included.

## 3.2. Management considered

The key management parameter considered for rewetting is WT depth (WT in meters below or above the surface). Deep WTs are typically associated with intensive agriculture, whereas shallow WT can represent non-intensive agriculture, most commonly grassland or paludiculture, i.e. the wet management of organic soils with water-tolerant plant species such as reed or typha), as well as natural peatlands. Most study sites include agricultural uses (cropland, grassland), as well as different forms of wet systems (restoration to natural conditions, paludiculture, riparian wetlands, and mires). In some locations reported in Tiemeyer et al., (2020), restored peatlands or mires, e.g. natural peatlands (bogs, fens), may include trees such as alder or pine. The dataset was not classified further into different management or land use types. The reasons for this are that **i)** Tiemeyer et al. (2020) did not find clear differences between the responses to WT in different land uses for $CO_2$, and **ii)** the large variety of systems, especially at shallow WT, makes any classification arbitrary. As the sites also differ in (former) mire type (mostly bog or fen) and climate, we do not further subdivide them. In this way, enough data points are available to also evaluate the effect of partial rewetting, e.g., raising the WT by only 10 or 20 cm.

## 3.3. Variables used

The underlying studies applied two widely used GHG measurement techniques, namely different forms of static chambers or eddy covariance systems. The carbon

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

balance of the fields includes both the $CO_2$ balance and the harvest export, hereafter referred to as NEP. NEP is an indicator of soil carbon balance. Possible carbon losses in the form of dissolved organic matter are included in the calculation of NEP in some studies. The NEP of all studies is expressed here as t $CO_2$-C $ha^{-1}$ $yr^{-1}$. Positive numbers indicate net carbon losses, negative numbers show net gains, i.e. sequestration. The methane balance is expressed as kg $CH_4$- C $ha^{-1}$ $yr^{-1}$. Positive numbers indicate net CH4 emissions, negative numbers net uptake, i.e. net methane oxidation.

$CO_2$ and $CH_4$ data are plotted as a function of WT. WT is given as an annual mean value in meters below the surface. Negative WT numbers indicate a WT below the surface, while positive numbers indicate a WT above the surface, i.e. flooding.

## 3.4. Analysis

All data from the references cited above were compiled in Excel spreadsheets from the original papers and their supplements, quality checked and, where necessary, converted to the same units. The data were then plotted together as a function of WT and a function was sought that best represented the observed variability. For NEP, the best result was obtained using a sigmoidal relationship with the WT, in accordance with Koch et al., (2023) and Tiemeyer et al., (2020). Evans et al., (2021) suggested a linear relationship between NEP and WT. Their data are included here, but the linear fit yielded a smaller $R^2$ than the sigmoidal fit when all data were considered together. For $CH_4$, a single exponential function fitted the data best, in agreement with Evans et al., (2021), Koch et al., (2023) and Tiemeyer et al., (2020).

The 95% confidence limits of the regression lines were taken to provide an estimate of the uncertainty in the comparison between deeply drained and rewetted sites. The relationship between WT and GHG fluxes was used to find the optimum WT for minimum GHG emission. This was achieved by converting $CH_4$ fluxes to $CO_2$ equivalents using a global warming potential GWP100 of 27 for methane (IPCC, 2021). For the drained counterpart, a WT depth of -0.60 m was chosen, as there is no further increase in $CO_2$ emissions below this point.

## 3.5. Co-benefits

Raising the WT of peatlands drained for agriculture typically affects intensive agricultural use and is associated with reduced income for the farmer. Additionally, induced land-use change to compensate for lost food or feed production may be an issue (Willenbockel, 2024). The extent to which products from paludiculture (e.g. wet management of organic soils) such as fibres or mosses, can replace foregone income from drained agriculture is highly context-specific and systems are still being developed. On the other hand, management of organic soils with higher WT, such as paludiculture or restoration to natural conditions, provides important benefits that are lacking when these soils are drained. These include a much better GHG balance, improved biodiversity, water retention and purification, and local cooling (Tanneberger et al., 2024).

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

## 3.6. Results

The results for NEP clearly show a decrease in soil carbon loss with increasing WT (Figure 4). While at a depth of -0.60 m or below, annual losses are about 8.2 t C / ha /yr, increasing the WT to the surface induces a small sink of 0.4 t C / ha /yr on average. NEP is particularly sensitive to WT in the range -0.40 to 0.00 m. The NEP-WT relationship was best described by a sigmoidal function as described in Figure 4.

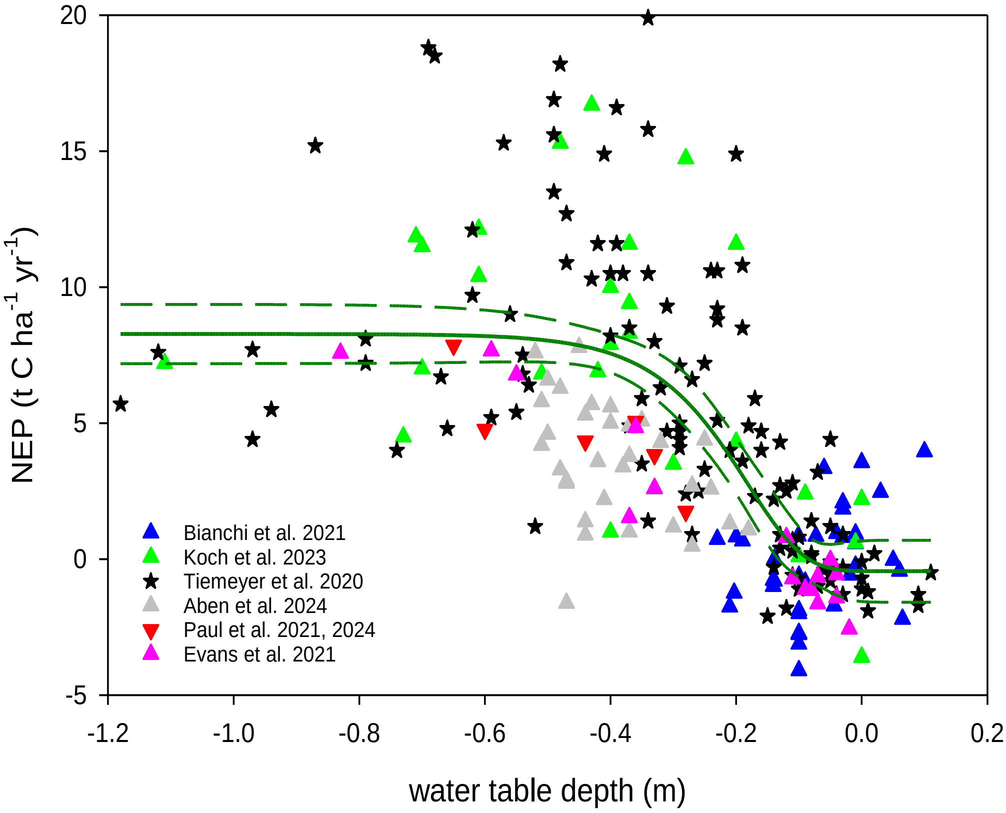



**Figure 4.** Relationship between water table (WT) depth and net ecosystem productivity (NEP) from drained and managed, rewetted and natural peatland sites in Europe.Curve (solid green line) shows sigmoidal fit to the data plus its 95% confidence interval (dashed green lines). The curve follows the function NEP = y0+a * exp(-exp(-(WT-x0)/b)) with y0 = -0.44 (0.58); a = 8.72 (0.87); x0 = -0.18 (0.02); b = -0.089 (0.0238) (values in parenthesis are one standard error). $R^2$ = 0.48.

For CH4, the previously reported exponential dependence of emissions on WT is confirmed (Figure 5 and regression equation in figure caption). While deep WT allows CH4 oxidation in soil or even net uptake from the atmosphere, flooding triggers very high CH4 emissions. A net CH4 emission can already occur at a WT above -0.44 m.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

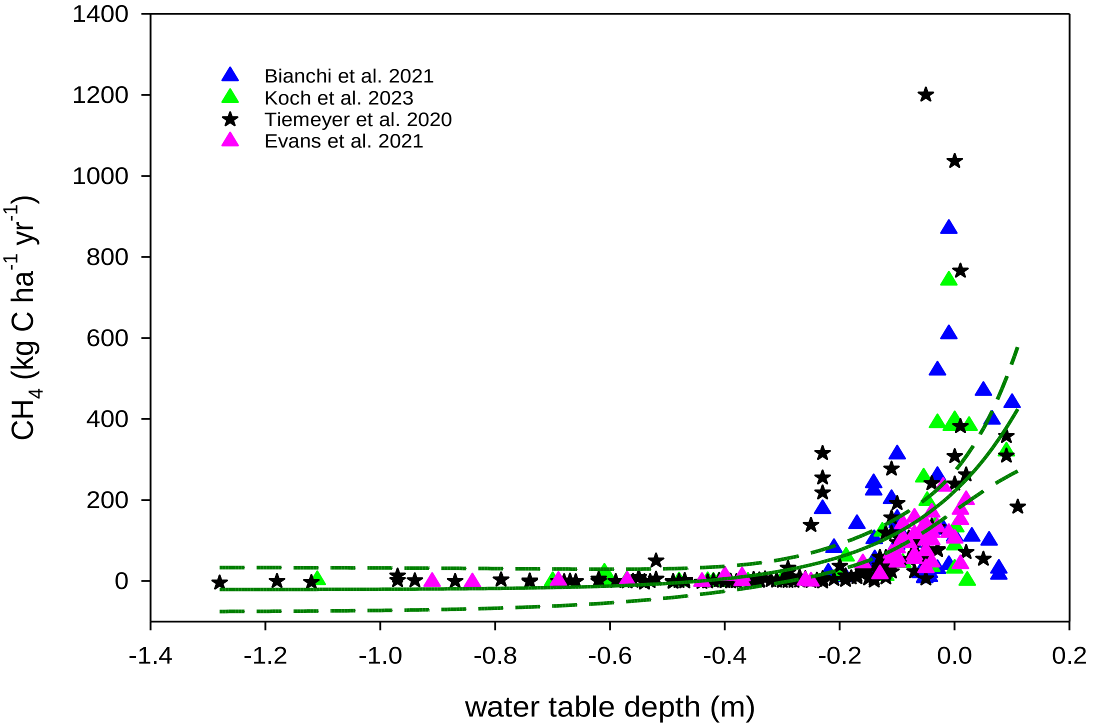



**Figure 5.** Relationship between water table (WT) depth and net methane flux from drained and managed, rewetted and natural peatland sites in Europe. Curve (solid line) shows exponential fit to the data plus its 95% confidence interval (dashed lines). The curve follows the function $CH_4$ = y0 + a * exp(b*WT) with y0 = -21.25 (27.72); a = 242.97 (36.66); b = 5.52 (1.52) (values in parenthesis are one standard error). $R^2$ = 0.28.

The GHG optimum for average $CO_2$ and $CH_4$-fluxes is 4.54 (range -0.12 – +9.00) t $CO_2$-eq. / ha / yr and is reached at a WT of -0.06 m (Figure 6). For comparison, the emission at -0.60 m is 29.66 (range 24.6 – 34.8) t $CO_2$-eq. / ha / yr, giving an average GHG saving potential of 25 t $CO_2$-eq per ha and year with rewetting. It should be noted that over longer time periods the cumulative $CO_2$ savings are closely related to the SOC stock in the peat.

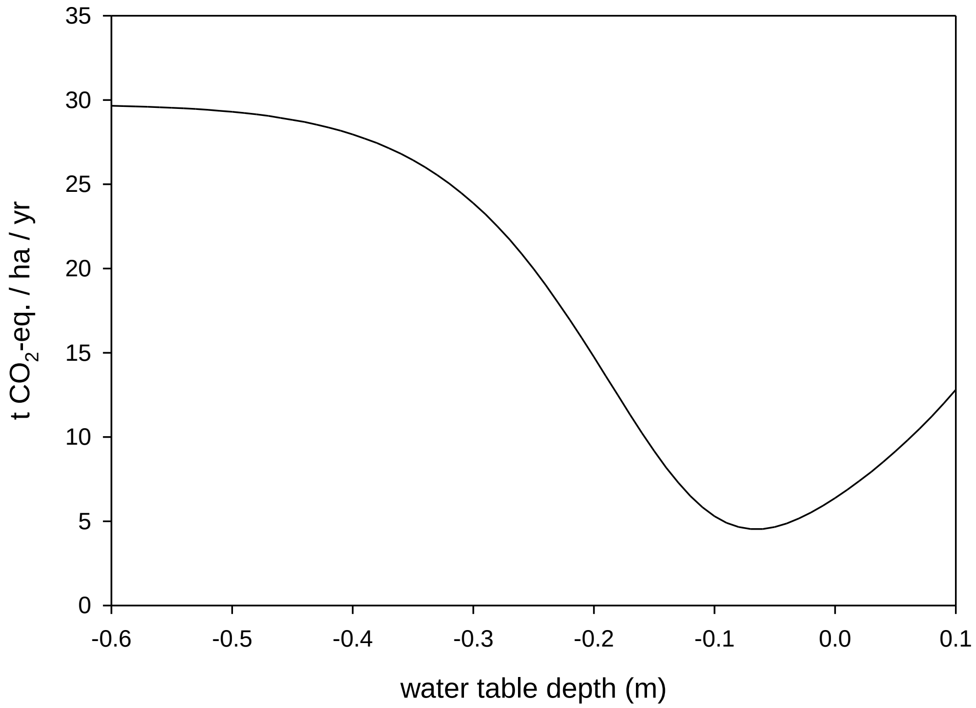



**Figure 6.** Optimum curve for GHG emissions from organic soils along the gradient of water table (WT) depth considering fluxes of $CO_2$ and $CH_4$.

The overall effect of changes in WT on the NEP and $CH_4$ balances of drained and wet peatlands is clearly documented in the references used for this analysis and highly significant ($p<0.01$). The WT explains 48% of the variability in the data for NEP and 28% for $CH_4$. It should be recalled that the data sets were not separated by land use or management as explained above. An important distinction is between fens (minerotrophic) and bogs (ombrotrophic), as their different pH and nutrient status affect GHG fluxes. However, the papers reviewed often make this distinction only for semi-natural systems, whereas for managed systems (e.g. at majority of the sites) only the land use type is reported, regardless of the underlying peatland type. Therefore, the regressions presented here do not replace site-specific measurements or estimates but rather provide a general overview of the mitigation potential of raising the WT.

$N_2O$ emissions from managed organic soils is typically several times higher than from similarly managed mineral soils. In contrast to mineral soils, most of the $N_2O$ comes from decomposing organic matter rather than from fertilisation (Wang et al., 2024). In general, $N_2O$ emissions from organic soils are related to several factors, such as soil C/N ratio, land use history and drainage, or peatland type (Lin et al., 2022). The latter study compiled 492 annual $N_2O$ flux data from Europe. However, $N_2O$ emissions do not follow WT as closely as $CO_2$ or $CH_4$ fluxes, although they tend to decrease with increasing WT (Figure 7). The overall weak relationship with WT prevents us from including $N_2O$ in the overall assessment. However, the data suggest a lower $N_2O$ emission at high WT, which was found to be significant for subsets of the data by Lin et al., (2022). Therefore, omitting $N_2O$ is a conservative approach in the context of rewetting projects in CF.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

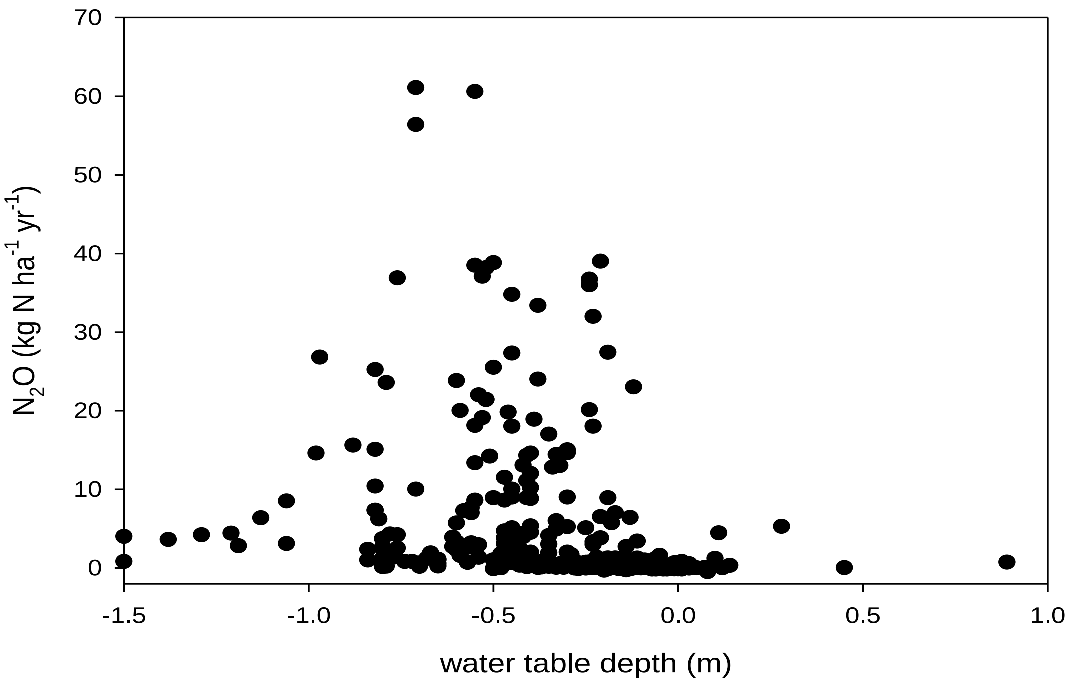



**Figure 7.** Overview of $N_2O$ flux data from European sites plotted as a function of WT (Lin et al., 2022).

Summary of co-benefits of mitigation practices by agricultural systems

In addition to the significant GHG emissions savings, the co-benefits of rewetting managed organic soils, e.g. former peatlands, to a natural state are thought to include improved biodiversity with species specific to peatland ecosystems, water retention in the landscape, water purification (particularly reduced dissolved organic matter leaching) and local cooling. In regions with few remaining natural peatlands, peatland restoration could also support recreational values. For rewetting combined with wet management, e.g. paludiculture for biomass and fibre production, carbon loss savings can be as high as for rewetting combined with natural restoration. Data in Bianchi et al., (2021) show that NEP for rewetting combined with natural systems or with paludiculture with sphagnum cultivation shows similar results (-1.30 ± 0.52 and -1.47 ± 0.24 t $CO_2$-C / ha /yr, respectively).

## 3.7. Discussion

A key aspect for MRV systems is the need to measure GHG fluxes rather than SOC stocks in peatland rewetting projects. First, unlike mineral soils, SOC losses or gains cannot be derived from SOC measurements per se unless the entire peat profile is repeatedly measured, which is not feasible in many cases given the peat thicknesses of several meters. Secondly, the role of $CH_4$ at high WT becomes a very important trade-off that needs to be quantified. Both gases can now be measured with high accuracy using either chamber or eddy covariance techniques. As for mineral soils, quantification


Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

of NEP requires measurement of harvest export and, where applicable, import of organic matter into the field.

A further important aspect is the sparse information on carbon lost through leachate (dissolved organic carbon, DOC). DOC is often not included in the above references used to derive NEP-WT relationships. DOC can be a significant proportion of the total C budget. IPCC (2014) suggests a generic DOC factor of 0.60 t C /ha /yr, which is higher than the DOC factors for natural systems in the boreal or temperate zone reported therein. As for $N_2O$, omitting DOC from the overall assessment in rewetting projects is therefore a rather conservative approach, as rewetting is likely to reduce not only $CO_2$ but also DOC.

## 3.8. Insights

Peatland rewetting is a measure with a high probability of significantly improving the GHG balance. In addition, large areas of former peatlands are being drained and managed, offering significant opportunities to reduce emissions from these soils (UNEP, 2022). In contrast to mineral soils, monitoring and validation is usually not possible with repeated SOC stock measurements. A reliable WT record is the easiest way to predict GHG from these systems. However, the proposed generic curves do not replace site-specific estimation or quantification. While groundwater measurements are necessary, they only provide an estimate with the uncertainty given above in the corresponding figures for NEP and $CH_4$. The gold standard would be direct field GHG measurements to account for site- or region-specific conditions. As an alternative, i) GHG estimates based on the vegetation have been proposed (Couwenberg et al., 2011). However, such an approach also requires region-specific calibration against measured GHG fluxes and expert knowledge. Secondly, GHG fluxes can be estimated using ecosystem models (e.g., Deng et al., 2015; Silva et al., 2024; Swails et al., 2022). As with vegetation or WT depth as proxies, calibration and validation procedures are required to obtain reliable estimates. In addition, the application of models requires considerable expertise. On the site of research, more specific response curves (WT vs. GHG) that take into account the effect of important drivers such as different peatland types and peat qualities, nutrient status, soil pH and climate zones are needed to better understand the large variability in the fluxes at the same WT.

At the technical or application level of rewetting, important aspects to consider include soil properties such as hydraulic conductivity, nutrient status, a list of site selection criteria (e.g. remaining peat deposit to be protected), or availability of water for rewetting. Drainage systems often extend over more than one field, so an assessment of the area affected by rewetting must be carried out beforehand. Taken together, the requirements for technology, expertise and skills are higher than for some of the typical mineral soil carbon sequestration measures, such as cover crops or improved crop rotations, which can be implemented by farmers themselves with little or no prior advice.

On the economic side, the loss of income from agricultural production and the costs of technical implementation needs to be weighed against the benefits of improved ecosystem services, incentive schemes, elimination of the need for drainage system maintenance etc. Possible solutions are site- and context-specific, require economic assessment, and can only be evaluated and possibly implemented in the context of the policy framework, which is often national or regional.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# 4. Arable lands

*Svoboda Adam[1], Panagea Ioanna[2], Torrús Castillo Milagros[3], Dankers Caroline[4], Holec Josef[1], Janků Jaroslava[1], Lesschen Jan Peter[4], Poláková Jana[1]*

*[1] Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Science Prague (CZU), Czechia*

*[2] Flanders research institute for agriculture, fisheries and food (ILVO), Belgium*

*[3] Spanish National Research Council (CSIC), Spain*

*[4] Wageningen Environmental Research, Wageningen University & Research, Wageningen, Netherlands.*

## 4.1. Methodology for information search.

We performed a systematic search for peer-reviewed meta-review studies on SOC stock change using SCOPUS, Web of Science, and Google Scholar search engines in March and April 2024. The focus was on meta-reviews due to our interest in information on carbon sequestration potentials already applicable in the European Union and the fact that the national, regional and experimental case studies would require immense theoretical effort to synthesise many different methodologies, variables and conditions. Our search was complemented by some empirical and model studies to fill the shortcomings in information provided by the meta-reviews.

The research queries were developed to include various agricultural practices (i.e., catch crops, crop rotations, intercropping, zero tillage, reduced tillage, reduced fertiliser and pesticide use, organic farming, set-aside, organic amendments and crop residue management, adding legumes, restriction on slopes, grass in orchards and vineyards, replacing annual with perennial/permanent crops) on arable land and their potential to sequester carbon (arable* AND "carbon sequestration*" AND "(selected agricultural practice)*"). This comprehensive approach aimed to capture a wide range of practices and insights from existing literature.

We screened the full text of 65 studies (243 entries) from 8 different geographical zones published during the last 25 years for their potential inclusion in this study (Figure 8).
To ensure quality and relevance, we established several stringent criteria for inclusion. Specifically, a study had to:

a) Be published in English to ensure accessibility and comprehensibility.
b) Include a statistical analysis with a well-documented methodology to guarantee the reliability of the findings.
c) Have at least part of the reviewed study conducted within the European Union or Europe, ensuring the relevance of the data to our geographic focus.
d) Investigate the impact of agricultural practices on SOC stocks, directly addressing our research objectives.

We screened the full text of 65 studies (243 entries) from 8 different geographical zones published during the last 25 years for their potential inclusion in this study (Figure 8).

Through this rigorous selection process, we retained 14 peer-reviewed studies (3 models and 11 meta-reviews) containing five different practices (catch and cover crops; crop rotations; reduced tillage; zero tillage and organic amendments and crop residue management).

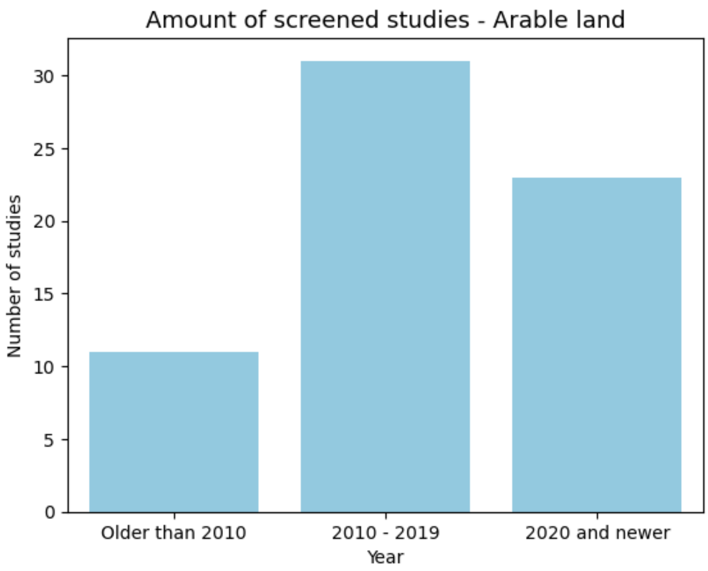



**Figure 8.** Number of arable land studies by year of publication.

The screening process considered several critical factors extracted from each study: agricultural practices, their impact on SOC, quantified carbon sequestration potential (expressed in appropriate units), control practice, sampling depth, duration of the study, and any additional notes deemed relevant.

## 4.2. Management considered

### Catch and cover crops

Catch and cover crops are grown in between cash crops, i.e. between the harvest of the preceding crop and the establishment of the subsequent crop to prevent soil erosion. They can directly be a part of the crop stand as under sowing intercropping or companion crops. Cover crops are mainly fast-growing species with relatively cheap seeds, which can produce sufficient biomass in a relatively short period to fulfil the required functions. Whereas in the past the biomass of intercrops was often used for feeding purposes, today it is usually incorporated into the soil. As a result, the soil is enriched with high-quality, rapidly decomposable organic matter and, in the case of legume intercrops, with organic nitrogen obtained through biological fixation.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Catch and cover crops can be sown as single species or as mixtures. The most cultivated species include those from the Brassica family, mainly white mustard, oil radish, and to a limited extent, rape or canola. Crimson clover, creeping clover and Alexandrian clover are often cultivated, as are vetches, peas and faba beans. Often grown are also phacelia, buckwheat, from cereals oats or sorghum, and from grasses mainly ryegrass species.

Catch and cover crops incorporate $CO_2$ into their biomass at a time when post-harvest residues of the main crop are decomposing. They increase the total amount of biomass produced, increasing the amount of organic matter entering the soil. This is particularly important for crops with small amounts of post-harvest residues, e.g. potatoes and vegetables. Fresh intercrop biomass is easily decomposable and is used as a source of energy and nutrients for the soil community, which transforms this biomass into more stable forms of organic matter.

Crop rotations

Crop rotation is the practice of growing a series of different types of crops in the same area across a sequence of growing seasons. The cultivation of annual crops requires the annual establishment of crop stands. It is then up to the farmer to decide whether to sow the same crop again (monoculture) or a different crop, i.e. crop rotation. Whether crops are grown in monoculture or regularly rotated is often based on the traditions of the farming system. Regular crop rotation became widespread in central and western Europe during the 18th and 19th centuries when clover and root crops were introduced in rotation with cereal crops, together with a reduction of fallowing. In recent decades, the number of crops in rotation has declined and the dominance of the most economically important crop species has increased, reducing the diversity of crop rotations.

Crop rotation reduces the negative effects of repeated cultivation of the same crop species. As a result, higher yields, better crop health and lower weed occurrence can be achieved. Crop rotation makes it possible to rotate species with shallow root systems with deep-rooting ones, species with low post-harvest residues with those that leave sufficient residues on the field. This reduces the negative effect of selected species on the amount of SOM. A well-designed crop rotation with crops that provide high C input in the soil or improved crop rotations with cover crops, and crops that increase the C inputs such as perennial crops increases the amount of organic matter (roots, aboveground post-harvest residues) entering the soil. Another positive aspect of crop rotation is the higher diversity of soil organisms - the higher the productivity of the soil community, the higher is the proportion of SOM.

Reduced tillage

Reduced tillage or conservation tillage is a soil tillage system without intensive soil reversion. While in a conventional tillage system, the basic tillage operation is ploughing, in reduced tillage ploughing is omitted altogether and is replaced with shallower or deeper cultivation without intensive soil reversion. In these systems, there is no need for the whole surface tillage. Non-inversion tillage systems intensively


Project MARVIC has received funding from the Horizon Europe
Programme under grant agreement no. 101112942

cultivate only the strips used for sowing the crop, while the rest of the field remains undisturbed. There is also a merging of individual working operations, most often seedbed preparation and sowing. Omitting ploughing means not only lower tillage costs but also greater protection of the land against erosion and better conditions for soil fauna.

In a reduced tillage system, post-harvest residues or intercrop biomass are not incorporated into the soil profile but remain either directly on the soil surface or just below it. This effectively protects the soil from erosion, reduces rapid mineralisation and thus provides a more stable source of food and energy for soil fauna. By limiting rapid mineralisation, organic matter accumulates in the surface layer of the soil, which can then be more easily converted into more permanent forms of SOM. The higher amount of SOM is also due to the higher biomass of soil organisms, which are not damaged by intensive soil cultivation.

Zero tillage

Zero-tillage is the practice of drill-seeding with no prior tillage of soil. Tillage has been used since the beginnings of agriculture to create suitable conditions for the crops grown - incorporating post-harvest residues and fertilisers, depositing seed at the required depth, and removing weed competition. Both conventional and reduced tillage systems are based on repeated soil cultivation. In the case of conventional ploughing systems, primary tillage involves turning the topsoil and intensive soil mixing. This is followed by seedbed preparation before sowing and, if necessary, soil cultivation during the growing season. Zero tillage systems omit tillage altogether. This means that there is no soil disturbance, better conditions for soil fauna and a reduced risk of soil erosion.

In a zero-tillage system, post-harvest residues remain on the soil surface, protecting it from erosion and unproductive evaporation. Leaving a layer of organic matter on the soil surface is closer to natural ecosystem conditions. As the post-harvest residues or intercrop biomass are not incorporated into the soil, they are not rapidly mineralised and thus provide a longer-term food source for soil organisms, which gradually incorporate the material from the surface deeper into the soil profile (earthworms). Also, the root system of plants is not subjected to rapid mineralisation, which contributes to increasing the amount of soil carbon in organic form. However, the accumulation of organic matter on the soil surface also makes it easier for diseases and pests to survive, and an increased susceptibility to weed occurrence, which in conventional agriculture leads to more intensive use of pesticides. It is also important to recognise that zero tillage slows down soil mineralisation and should be paired with other agricultural practices that actively sequester carbon to achieve effective carbon sequestration.

Organic amendments and crop residue management

Intensive agriculture is characterised by low inputs of organic matter into the soil. Organic matter can be supplied to the soil mainly in the form of post-harvest residues when additional plant parts are not harvested as the main product but left on the surface or incorporated in the soil. Other forms of post-harvest residues include catch crop biomass or organic manures, and biogas plant waste. Mixed farms with livestock can

return a significant part of their production to the field in the form of manure, while farms specialising in crop production can address the lack of organic fertiliser by consistently incorporating post-harvest residues, more frequent planting of catch crops or by purchasing, for example, composts.
Organic amendments consist of organic materials originating from biomass or living organisms. Typically, this includes compost, wood chips, biochar, animal manure, straw, husks, geotextiles, and sewage sludge. These materials are rich in organic matter and essential macro- and micronutrients, which enhance soil fertility by improving microclimatic conditions and can also serve as substrates for microbial activity. The use of mulch on the surface of a dump notably impacts rhizosphere temperature and moisture levels.

The organic matter in the soil undergoes gradual mineralisation, decreasing steadily without further inputs. For most crops (except for some vegetables), only part of the biomass produced by the plant is harvested and the rest remains on the field as post-harvest residues. In the case of grains, this is the root system and part of the above-ground biomass, excluding seeds. in the case of root crops, it is the whole above-ground biomass and part of the root system. Most often, post-harvest residues are incorporated into the soil where they increase the amount of organic matter and support the biomass of the soil community as a source of food and energy. Post-harvest residues can be used as a by-product, for example as feed and bedding on the farm itself, then returned to the soil as manure. But they can also be sold to other farmers or used for energy purposes (straw). In this case, only a small part of the biomass produced is returned to the soil. In extreme cases, post-harvest residues may be burned, but this is not common in European agricultural practice. When growing crops with less post-harvest residues, it is advisable to include intercropping.

## 4.3. Variables used

The screening process considered several critical factors extracted from each study: agricultural practices, their impact on SOC, quantified carbon sequestration potential (expressed in appropriate units), control practice, sampling depth, duration of the study, and any additional notes deemed relevant.

During the systematic analysis of the published studies, the values and units of SOC storage reported by each study were recorded. The primary focus was on variables that provide quantifiable measures of carbon sequestration, which are essential for assessing the impact of different agricultural practices on SOC stocks.
The recorded variables were:

Annual SOC stock change rate (t C/ha/yr; t $CO_2$/ha/yr)
SOC concentration (g C/kg soil; %)

To facilitate a coherent and unified analysis, it was necessary to convert all values from selected studies to a common unit: tons of carbon per hectare per year (t C/ha/yr). This allows for direct comparison across different studies and variables by eliminating the disparity that arises from using different units, thereby ensuring all data points are

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

evaluated on the same scale. Moreso, the unit t C/ha/yr is highly relevant to agricultural studies, as it provides a direct measure of the amount of carbon sequestered per unit area over a given time period.

The usage of common and well-known units simplifies the presentation of results, making it easier for stakeholders, policymakers, and researchers to understand, interpret and compare the findings.

Almost all carbon sequestration potentials from the selected European studies were in t C/ha/yr, except for two studies that used t $CO_2$e/ha/yr. This was converted using the following conversion:

1 ton of $CO_2$e emissions = 1 ton × 12/44 = 0.27 tons C emissions

## 4.4. Analysis

The selected studies provided comprehensive information on the observed impact of various agricultural practices on carbon storage. Descriptive statistics were employed to analyse the data. In instances, where a range of values was reported, the mean value was utilised to ensure consistency and comparability across studies. For visual comparison and better interpretation of the results, the values were represented in graphical form using box and scatter plots. These visualisations were created using the Seaborn library in Python.

Box plots were used to effectively highlight the central tendency, variability, and the presence of outliers across different studies. The authors of the studies are provided in the legend for reference. The individual plots represent the lower quartile value (Q1), and the upper quartile value (Q3), with outliers denoting the minimum data value and maximum data value.

Scatter plots were used to present the carbon storage at the different soil depth at which sampling was conducted. Studies were categorised based on these soil depths, while individual depths represent the studies, with the authors listed in the legend. The x-axis of the scatter plot indicates the various soil depths (e.g. 0-30 cm, NA – soil depth information not available), while the y-axis shows the carbon sequestration potential in t C $ha^{-1}$ $year^{-1}$. This visualisation allows a comparison of carbon storage across different depths, providing insights into how soil depth influences carbon storage. Additionally, the scatter plot can help identify patterns or trends that are not immediately evident in tabular data.

## 4.5. Results

Figure 9 shows the sequestration potential for catch and cover crops as reported by each study. Seven studies were selected, two published before 2010, three between 2010-2019 and two after 2020. All studies that met the requirements showed a positive effect on the SOC annual change rate. Catch/cover crops generally have a positive impact on SOC storage, with quantified potentials ranging from 0.0837 to 0.35 t C/ha/yr. The lowest value, 0.0837 t C/ha/yr, is reported in the study by Frelih-Larsen et al. (2008), while the highest, 0.35 t C/ha/yr, is reported by Jarecki & Lal (2003). The median is set at 0.24 t C/ha/yr, while the mean value is 0.23 t C/ha/yr. Studies using a model to quantify carbon sequestration (Frelih-Larsen et al., 2008 and Lugato et al., 2015) generally report lower values (0.0837 and 0.18 t C/ha/yr respectively) compared to other catch and cover crop studies.

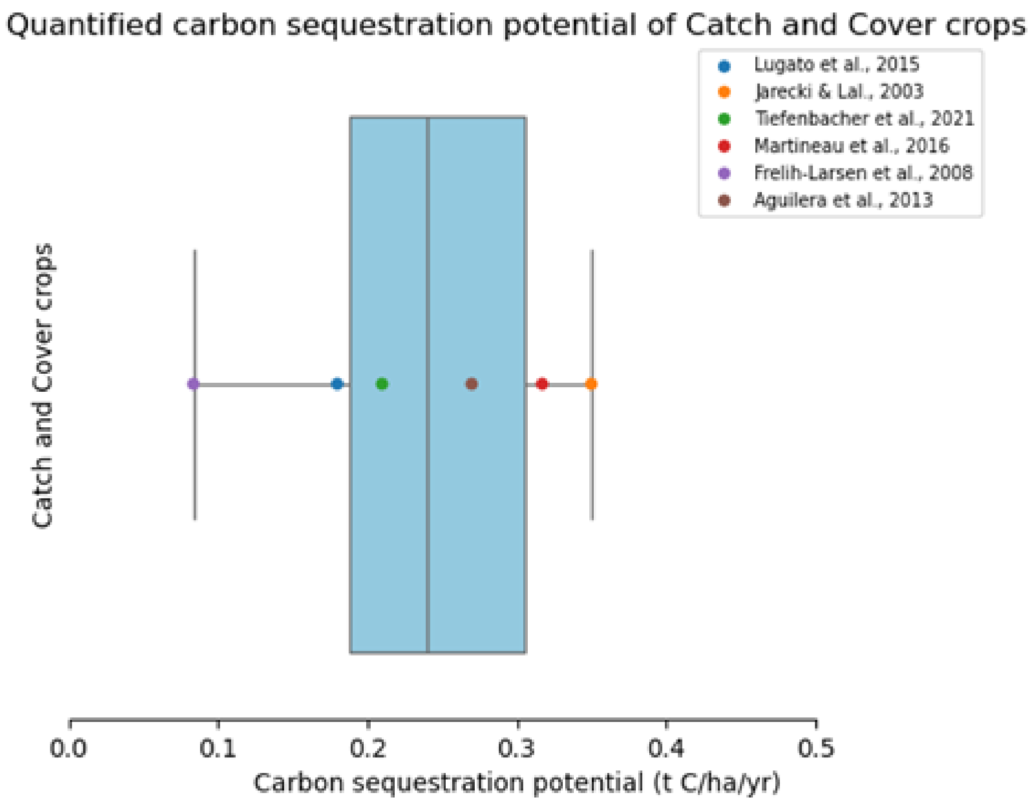



**Figure 9.** Quantified carbon sequestration potential of Catch and Cover crops. References are provided in the legend. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

The scatter plot that divides the studies according to the soil sampling depth (Figure 10) shows that the highest mean value of carbon sequestration, 0.31 t C/ha/yr, was recorded by studies that were carried out at a depth of 20–25 cm. For depths 0–25 cm and 0–30 cm, respectively, the results varied slightly. In the first case, the value was 0.21 t C/ha/yr and in the second one, the value was 0.18 t C/ha/yr. For the studies that did not report soil depth, large differences between the values can be seen.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

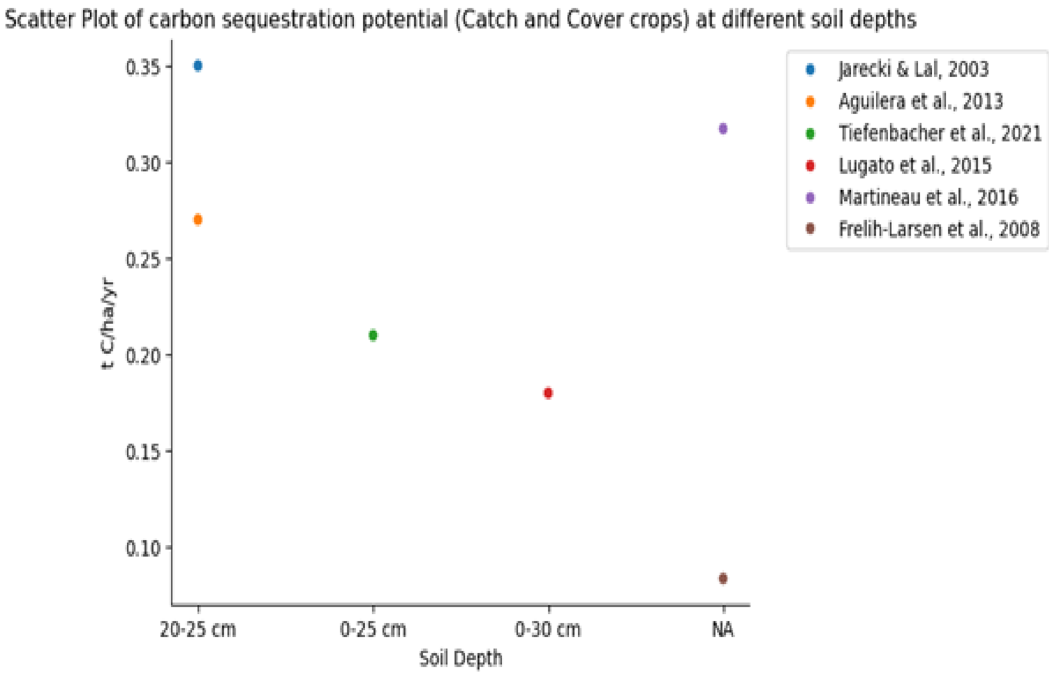



**Figure 10.** Carbon sequestration potential of catch and cover crops at the different reported soil depths. The x-axis indicates the various soil depths (e.g., 0-30 cm, NA). The y-axis shows the carbon sequestration potential in t C/ha/year.

Figure 11 shows the sequestration potential of crop rotations by selected studies. Six studies were selected, three published before 2010, two between 2011–2019 and one after 2020. All studies confirm a positive impact on SOC content. Crop rotations are generally associated with a positive impact on SOC sequestration, with quantified potentials ranging from 0.0945 to 0.5 t C/ha/yr. Frelih-Larsen et al. (2008) showed the lowest annual potentials, specifically 0.0945 t C/ha. At the other end of the spectrum are the papers by Tiefenbacher et al. (2021) and Smith et al. (2005) with reported potentials of 0.475 and 0.5 t C/ha/yr. The median is set at 0.165 t C/ha/yr and the mean at 0.258 t C/ha/yr. Studies using a model to quantify carbon sequestration (Frelih-Larsen et al., 2008; Lugato et al., 2015) report values around minimum and median (0.0945; 0.17 t C/ha/yr respectively).

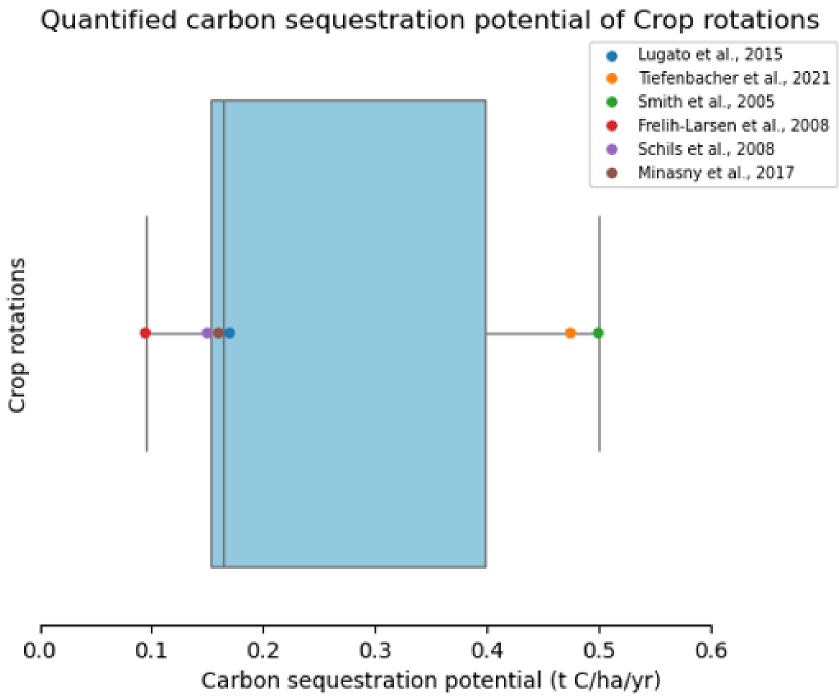



**Figure 11.** Quantified carbon sequestration potential of Crop rotations. References are provided in the legend. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

A scatter plot dividing carbon sequestration potentials by soil sampling depth (Figure 12) shows the difference between depths. The studies in which soil depth was set at 0-30 cm corresponded with their median (0.165 t C/ha/yr) to the overall median of all studies on crop rotations.

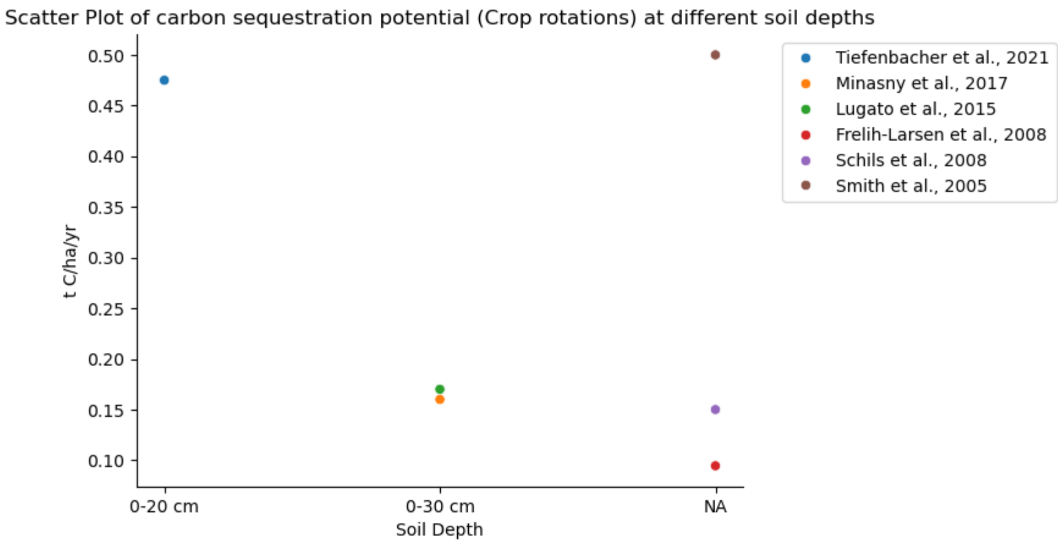



**Figure 12.** Carbon sequestration potential of Crop rotations at different soil depths. The x-axis indicates the various soil depths (e.g., 0-30 cm, NA). The y-axis shows the carbon sequestration potential in t C/ha/year.

The results of 10 selected studies for the management option of reduced tillage that met the set requirements can be found in Figure 13. Four studies are from before 2010, and six are from 2011–2019. The distribution is slightly more even than for crop rotations. Reduced tillage is generally associated with positive impacts on SOC sequestration, with quantified potentials ranging from 0 to 0.4 t C/ha/yr. The lowest values of 0 and 0.003 t C/ha/yr, respectively, come from Minasny et al. (2017) from a study conducted in Belgium over a 20-year cycle and Martineau et al. (2016) The result from Minasny et al. (2017) is the only one that does not show a positive effect of reduced tillage on SOC stocks, suggesting that reduced tillage may not always lead to measurable increases in SOC under certain conditions. The highest sequestration value of 0.4 t C/ha/yr is shown by Freibauer et al. (2004) in the topsoil, i.e. at a depth of 0–30 cm. The median is set at 0.225 t C/ha/yr and the mean at 0.192 t C/ha/yr. Studies using a model to quantify carbon sequestration (Vleeshouwers & Verhagen, 2002; Frelih-Larsen et al., 2008; Lugato et al., 2015) reported different values. A study by Vleeshouwers & Verhagen reported values of 0.25 t C/ha/yr (slightly higher than median), whereas Frelih-Larsen and Lugato showed 0.0675 and 0.1 t C/ha/yr respectively (lower than median).

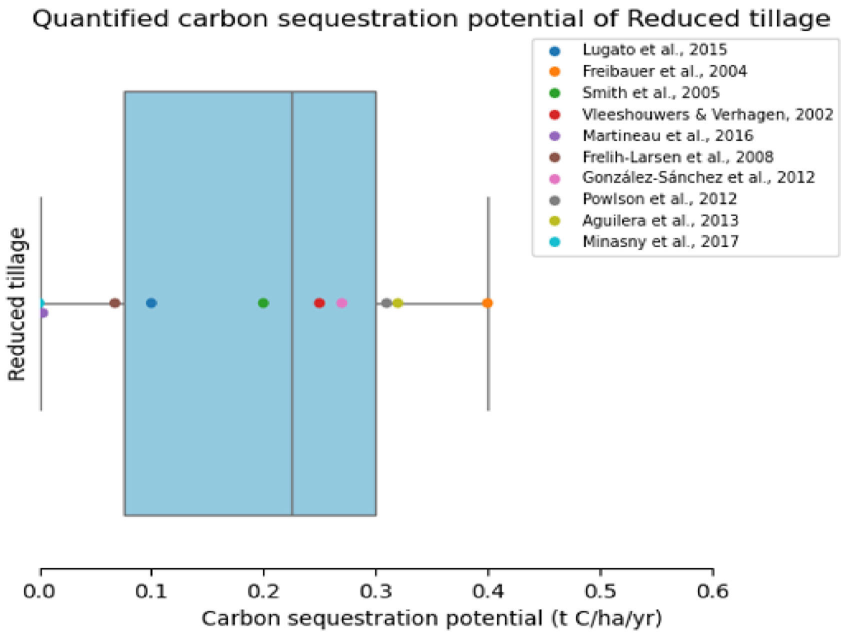



**Figure 13.** Quantified carbon sequestration potential of Reduced tillage. References are provided in the legend. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

When the values are divided by soil sampling depth (Figure 14), studies with a declared depth of 0 – 30 cm and studies without a specified depth have a relatively wide range. For the 20 – 30 cm depth, the average value is 0.29 t C/ha/yr, which is similar to the value from depth 40 – 52 cm of 0.27 t C/ha/yr. Even so, it is slightly higher than the median and mean, which were driven down by studies that reported very low annual carbon gains.

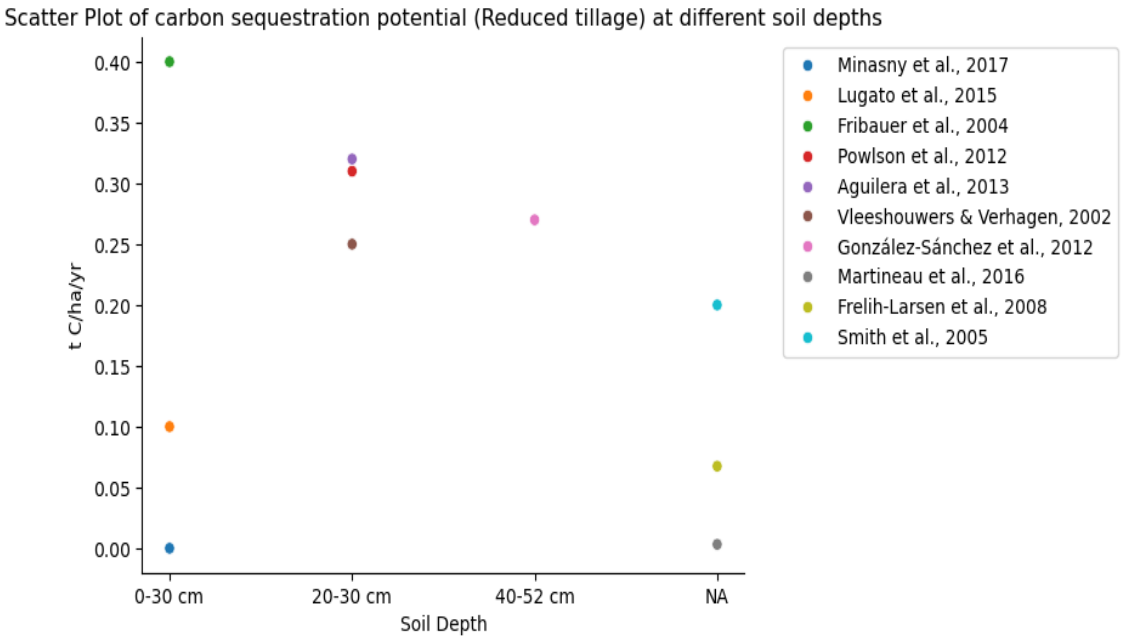



**Figure 14.** Carbon sequestration potential of reduced tillage at the different reported soil depths. The x-axis indicates the various soil depths (e.g., 0-30 cm, NA). The y-axis shows the carbon sequestration potential in t C/ha/year.

The carbon sequestration values obtained by zero-tillage are shown in Figure 15. Five studies are from before 2010, and three studies are from 2011–2019. Zero tillage appears to be an effective practice for enhancing SOC storage, with quantified potentials ranging from 0.2 to 0.64 t C/ha/yr. The positive impacts are consistent across various studies, though the results can differ due to specific conditions and methodologies used in the research. The study by Minasny et al. (2017), showed the lowest values, with an annual sequestration rate of 0.2 t C/ha/yr based on 20 years of measurement in France. On the contrary, the highest values, 0.64 t C/ha/year, were reported by a study from Spain conducted by González-Sánchez et al. (2012) combining no-tillage with crop rotation. This study is shown as an outlier beyond whiskers. The median and mean are calculated at 0.4 t C/ha/yr. A study using a model to quantify carbon sequestration (Frelih-Larsen et al., 2008) reported a generally lower value (0.26 t C/ha/yr) than most of the other studies.

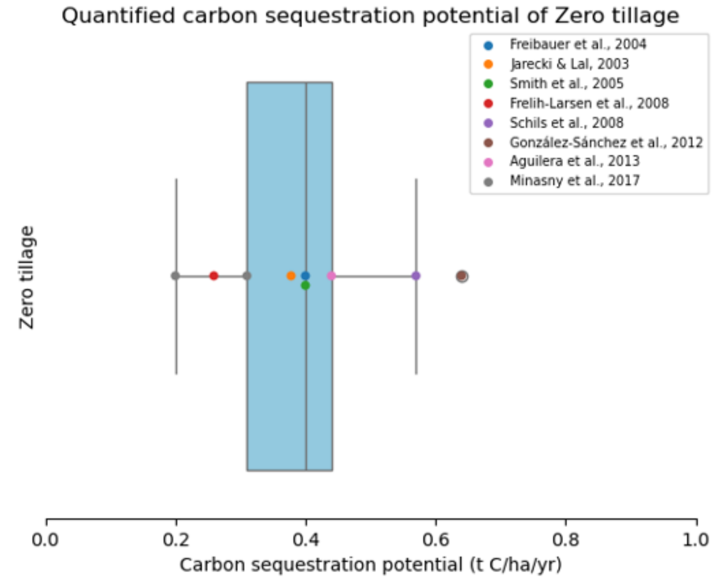



**Figure 15.** Quantified carbon sequestration potential of zero tillage. References are provided in the legend. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

The distribution of values by depth can be seen in Figure 16. The highest value was recorded, as already mentioned, by González - Sánchez et al. (2021) at a depth of 40–52 cm. At the same time, for studies where the depth was not specified, the values are evenly distributed. The studies without specified depth (mean 0.41 t C/ha/yr) and the 20–25 cm depth with mean carbon sequestration potential of 0.41 t C/ha/yr are closest to the median and mean values, respectively.

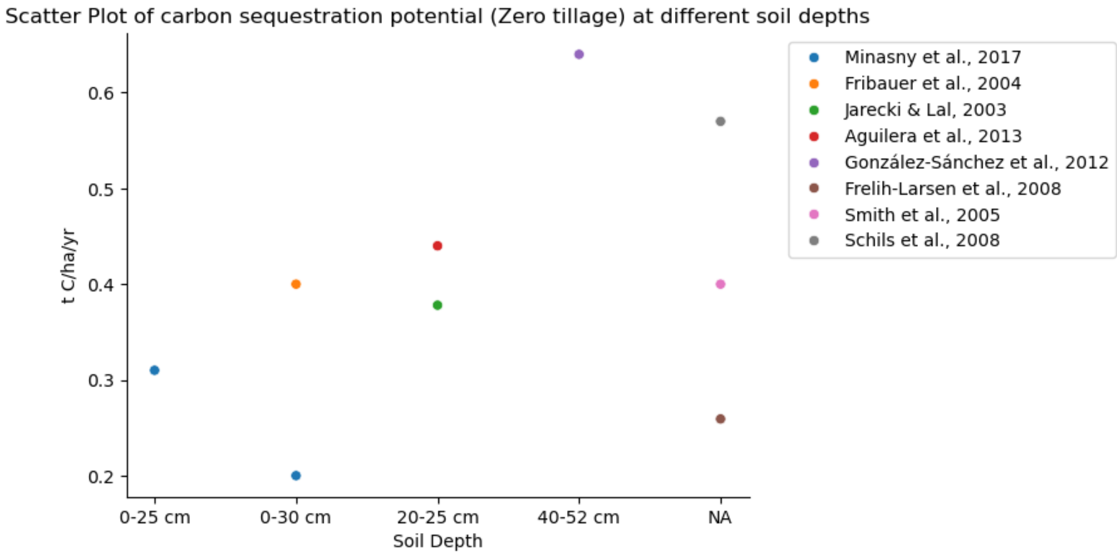



**Figure 16.** Carbon sequestration potential of Zero tillage at different soil depths. The x-axis indicates the various soil depths (e.g., 0-30 cm, NA). The y-axis shows the carbon sequestration potential in t C/ha/year.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

The carbon sequestration values of using organic amendments and implementing appropriate crop residue management can be seen in Figure 17. Model-based studies by Frelih-Larsen et al. (2008), Lugato et al. (2015), Vleeshouwers & Verhagen (2002), and review by Freibauer et al. (2004) report low values between 0.09–0.20 t C/ha/yr, while those by Vicente-Vicente et al. (2016), Smith et al. (2005), and Freibauer et al. (2004) report high values in the range of 0.65–0.7 t C/ha/yr. Thus, the overall range of values is 0.0945–0.7 t C/ha/yr, the median is set at 0.18 t C/ha/yr and the mean at 0.34 t C/ha/yr.

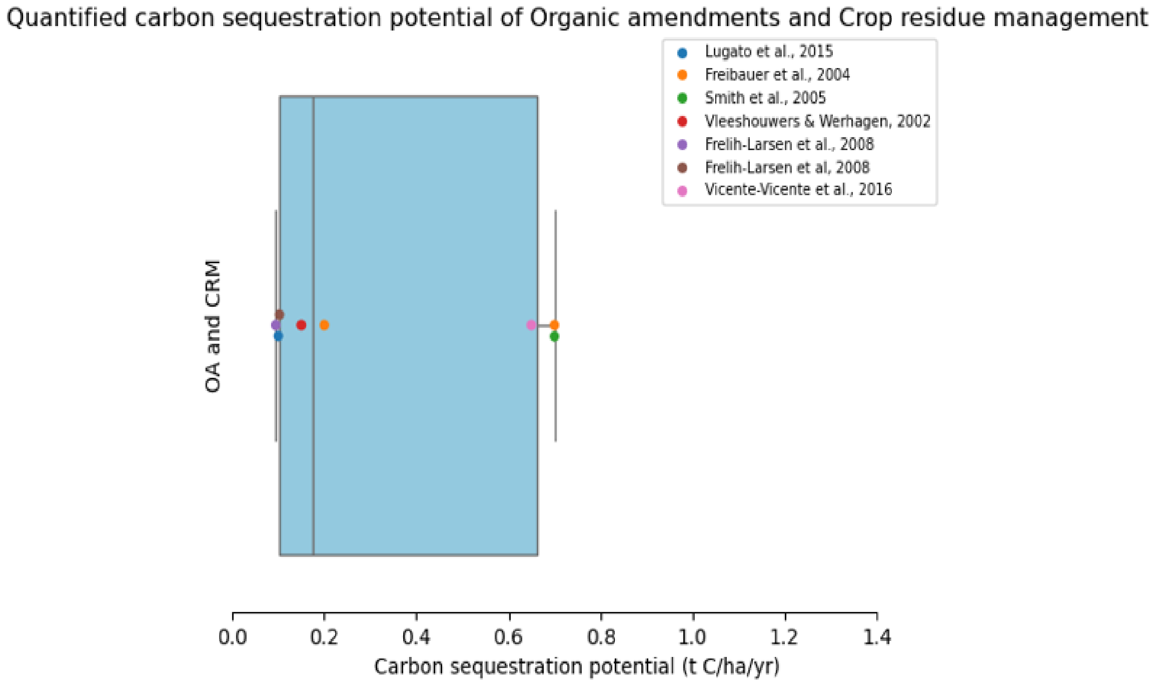



**Figure 17.** Quantified carbon sequestration potential of Organic amendments and Crop residue management. References are provided in the legend. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

The distribution of reported carbon sequestration values for studies that reported soil sampling depth of 0 –30 cm and those that did not specify soil sampling depth were widely distributed (Figure 18). The average is 0.28 t C/ha/yr in the 0–30 cm depth studies and 0.386 t C/ha/yr in the studies with no specified depth.

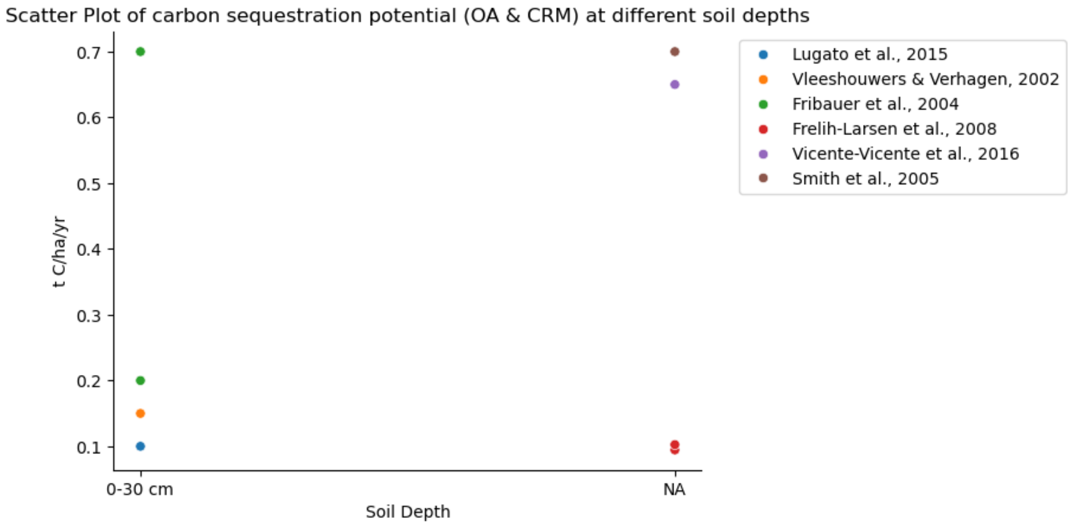



**Figure 18.** Carbon sequestration potential of Organic amendments and Crop residue management at different soil depths. The x-axis indicates the various soil depths (e.g., 0-30 cm, NA). The y-axis shows the carbon sequestration potential in t C/ha/year.

## 4.6. Co-benefits

Catch and cover crops prevent soil erosion and reduce runoff by covering the soil in the intercropping period, improving soil structure, thus increasing infiltration and reducing nitrate leaching by temporal nutrient immobilisation. They can also reduce weed occurrence on the field and decrease the infestation of following crops by pests and diseases. They promote the overall biodiversity in agroecosystems, supporting soil biota, pollinators, and vertebrates (Sharma et al., 2018).

Crop rotations increase SOC, microbial activity and diversity, increase yields, improve pest control, provide better weed control and soil health, reduce runoff and soil erosion, increase nutrient availability, and benefit biodiversity and water (Yu et al., 2022).

The benefits of reduced tillage are region-specific. It may improve productivity via improved moisture retention, as well as reduce fossil fuel use, increase soil water retention, increase binding of pollutants by soil and favour biodiversity in the soil (Smith et al., 2008).

A co-benefit of zero tillage can be considered the lower usage of fossil fuels. In dry areas, zero tillage may improve productivity via improved moisture retention (Holland, 2003; Kumari et al., 2023).

Organic amendments and crop residue management offer a wide range of benefits, as reported by scientists, including higher long-term soil fertility, wildlife and biodiversity promotion (Turmel et al., 2015; Aytenew & Wolancho, 2020).

Summary of co-benefits of mitigation practices by agricultural systems

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

**Table 10.** Drivers affecting sequestration variability, adaptation, benefits, trade-offs effect on productivity and reference of the main management practices of arable lands.

| | Drivers affecting variability | Climate benefits – adaptation | Benefits |
|---|---|---|---|
| **Catch crops** | Type of catch/cover crop; climate and weather conditions; agricultural practices used; soil fertility and health; geographical and local factors | Improved soil structure, water infiltration and water holding capacity and pest resilience | Catch crops prevent soil erosion, reduce runoff, and improve soil structure, thus increasing infiltration and trapping nutrients reducing nitrate leaching |
| **Crop rotations** | Climatic factors, soil properties (soil texture, pH, soil depth), agronomic practices (monoculture crops, rotation crops, rotation cycles, rotation length, tillage) | Reduction of pest and pathogen risks; preservation and improvement of the productive capacity of soils; reduction of impacts from flooding and droughts | Increased SOC, microbial activity and diversity, increased yields, improved pest control, higher weed control and soil health, reduced runoff and soil erosion, increased nutrient availability, and benefits to biodiversity and water |
| **Zero tillage** | Climate, soil texture, crop type, duration since tillage abandonment, residue management, crop rotation, nitrogen fertilisation | Higher resilience against weather extremes due to soil erosion reduction and soil water capacity increase | Less fossil fuel is used. Dry areas may improve productivity via improved moisture retention. Benefits water conservation, soil quality and biodiversity |
| **Reduced tillage** | Climatic condition, SOC content, soil texture, crop types, residue management, crop rotation, nitrogen fertilisation | Higher resilience against weather extremes due to soil erosion reduction and soil water capacity increase | Effects are regionally specific. Dry areas may improve productivity via improved moisture retention. Reduce fossil fuel use, increase soil water retention, increase binding of pollutants by soil and favour biodiversity in the soil |
| **Organic amendments & crop residue management** | Residue quality, health of the previous crop, potential susceptibility of the next crop and management options such as cultivar sections, crop rotations, and plant date | Improved soil structure, water holding capacity and soil erosion protection | Possible better long-term soil fertility/quality, SOC enhancement, soil moisture retention, nutrient cycling, and reduced soil erosion. Benefits biodiversity and energy conservation |

| | Trade-offs | Effect on productivity | Reference |
|---|---|---|---|
| **Catch crops** | Source of soil GHG emissions ($N_2O$, $CO_2$), catch crop cultivation is not | Generally positive (increased crop yield), may not be as | Freibauer et al., 2004; Tiefenbacher et al., 2021; Smith and Olesen, 2010; |



Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

| | | | |
|---|---|---|---|
| | always possible. Without adding organic matter (crop residues, organic fertilisers) the SOC decreases markedly after 10 years. Some catch crops can lead to a decrease in N uptake by following cereals, and increasing soluble P. Reduced available soil water for cash crops | productive as high fertiliser application. In some cases, catch crops may reduce available soil water for cash crops and thus negatively affect yields | Frelih-Larsen et al., 2008 |
| **Crop rotations** | Possible less available water for subsequent crops | Positive - Improved productivity in the medium term | Rosa-Schleich et al., 2019; Abdalla et al., 2016; Frelih-Larsen et al., 2008 |
| **Zero tillage** | Some increase in pesticide use. $NO_2$ emissions may increase as soils may become more anaerobic - more $N_2O$ production from denitrification. In wetter areas more risk of fungal attack, reduced emergence and crop failure. High initial equipment cost | Positive, may be associated with difficult weed control | Abdalla et al., 2016; Freibauer et al., 2004; Frelih-Larsen et al., 2008 |
| **Reduced tillage** | Effects are regionally specific. Increased bulk density. Some increase in pesticide use. $NO_2$ emissions may increase as soils may become more anaerobic - more $N_2O$ production from denitrification. In wetter areas more risk of fungal<br><br>attack, reduced emergence and crop failure | Positive, may be associated with difficult weed control | Abdalla et al., 2016; Freibauer et al., 2004; Smith et al., 2008; Frelih-Larsen et al., 2008 |
| **Organic amendments & crop residue management** | Promote N mineralisation and potentially enhance $N_2O$ and $CH_4$ emissions. Conflicting goals - retention of crop residues for increasing SOC versus using residues for energy production must be considered. Additional energy costs are required for chopping and incorporating residues | Positive. Soil fertility is maintained by returning crop residues and organic amendments | Freibauer et al., 2004; Tiefenbacher et al., 2021; Kragt & Robertson, 2014; Smith et al., 2008; Frelih-Larsen et al., 2008 |

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# 4.7 Discussion

### *4.7.1 Discussion of the results for arable lands*

Uncertainty in carbon sequestration studies arises from methodological differences, varying pedoclimatic conditions (Brombin et al., 2020), and special experimental factors like soil sampling depth (Olson & Al-Kaisi, 2015) and sequestration duration (West & Six, 2007).

When it comes to cover crops, different species and varieties have varying capacities to sequester carbon (Jian et al., 2020; Moukanni et al., 2022; Joshi et al., 2023), and their effectiveness can differ based on local conditions. The choice of cover crop species, for instance, can significantly influence the amount of biomass produced and, consequently, the amount of carbon that is sequestered in the soil. Certain species might be more effective in specific climates or soil types (Jian et al., 2020; Joshi et al., 2023), thus making their performance highly context dependent. Carbon sequestration can also be affected by the duration for which the cover crops are left to grow before termination (Moukanni et al., 2022; Joshi et al., 2023).

In crop rotations the choice of crops, including their carbon inputs and residue characteristics, can vary widely, affecting carbon sequestration (Skinuliene et al. 2024). The length and complexity of the crop rotation also play a significant role, with longer and more diverse rotations generally being more beneficial for soil carbon levels (Heikinnen et al., 2022).

The degree of soil disturbance and the frequency of reduced tillage practices can affect soil carbon sequestration (Krauss et al., 2022). Different soil types respond differently to reduced tillage, influencing carbon storage capabilities (Tobiašová et al., 2023). The effect of zero tillage on SOC stocks can be significant, however, over time, zero tillage can lead to soil compaction (Sarauskis et al., 2014), which might reduce its effectiveness in sequestering carbon (Brevik et al., 2002). While zero tillage has been widely promoted for its potential benefits in enhancing soil carbon storage, literature suggests that when the entire soil profile is considered, there is often no net carbon sequestration (Haddaway et al., 2017).

The type of organic amendments plays a crucial role, as different amendments have varying carbon contents and decomposition rates, leading to different sequestration potentials (Wu et al., 2024). Similarly, different crop residues have different carbon sequestration potential (Jarecki & Lal, 2003). Additionally, environmental conditions, such as temperature and moisture, affect the rate at which crop residues decompose (Huang et al., 2021) and contribute to SOC.

A meta-review of CF systems implemented by 12 private or public companies has demonstrated the carbon removals from agricultural soils to show that their outcomes are driven by administrative costs, different monitoring methodologies, and the extent of standardizing the verification of offsets and that these factors have variability depending

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

on the different types of practices implemented and system providers (McDonald et al. 2021a; 2021b).

Soil scientists have alerted us to the intermediate impact that sequestration practices have on the complex environment of agricultural soils, including plants, fungi and bacteria. This influence depends on a variety of factors such as soil type, soil depth, rock fraction and climate. Carbon sequestration takes years to decades, while at the same time, there is a likelihood of reversal (Hepburn et al. 2019). Furthermore, long-term changes in soil carbon content over thousands of years in this dynamic environment could likely outweigh the effects of agricultural practices.

There is ample literature on the sequestration potential of agricultural practices based on experimental case studies at regional and member-state levels. We focused on EU-level reviews of sequestration potential in arable soils and we found that there is a paucity of long-term studies that explore the lasting effects of various agricultural practices, particularly those published in Europe after 2020. This calls for caution in predicting the sustainability of carbon sequestration efforts over extended periods. Additionally, the wide variability in soil types and climatic conditions across arable lands presents another challenge. Differences in soil texture, organic matter content, and moisture levels can significantly affect how carbon is stored, while climatic factors like temperature, precipitation, and seasonal variations influence the effectiveness of agricultural practices.

Key agricultural practices, including crop rotation, cover cropping, reduced tillage, and zero tillage, are known to impact soil carbon levels. However, the specific mechanisms and interactions that determine their effectiveness still require further investigation. Fertilisation practices, particularly the use of synthetic fertilisers versus organic amendments, also pose significant knowledge gaps regarding their influence on carbon sequestration. Moreover, there is a need for more reliable and scalable techniques to monitor and verify carbon sequestration efforts effectively.

Finally, the ongoing effects of climate change on carbon sequestration in arable soils are not fully understood. Changes in temperature, precipitation patterns, and extreme weather events could alter soil carbon dynamics in manifold ways, complicating efforts to manage and enhance carbon storage in agricultural systems. This aspect will be further analysed in Task 4.5 of the MARVIC project.

### *4.7.2 Contextual remarks with regard to CarboSeq and other projects*

Compared to our approach focussing on the analysis of meta-reviews with EU focus, to the EJP SOIL CarboSeq project, an extensive review of European Long-Term Experiments (LTEs) was conducted to estimate emission factors for various management practices compared to control scenarios. The study also evaluated potential implementation areas for each practice and their corresponding annual carbon sequestration rates, accounting for technical and biophysical constraints.

Emission factors represent the relative change in SOC stocks under a specific management practice compared to a control scenario, with higher values indicating greater SOC increases. Based on mean emission factors, in arable systems, zero tillage compared to inversion tillage showed notable potential, with emission factors of 1.14 (fixed depth) and 1.11 (equivalent soil mass), exceeding the IPCC range of 1.03–1.10. Bai et al. (2018) reported a ratio of 1.2. The incorporation of straw residues left in the field versus their removal (EF = 1.09) also enhances SOC. Other practices included increasing forage legumes in rotations (EF = 1.08), using cover crops versus no cover crops (EF = 1.06), and non-inversion tillage compared to inversion tillage (EF = 1.05 fixed depth; EF = 1.03 equivalent soil mass), consistent with IPCC values (0.98–1.05). Bai et al. also reported high response ratios for crop rotation versus monoculture (1.25) and organic amendment addition versus no addition (1.29) in Europe and China.

In a global meta-review by Beillouin et al (2023), addition of organic amendments compared to mineral fertilisers was the practice with the highest per ha sequestration potential. Perennial crops and agroforestry showed also high SOC gains, while crop residue retention and cover crops provided smaller but positive effects. No/reduced tillage and crop rotation demonstrated slight improvements, while practices like plastic film mulching, species mixtures, mineral fertilisation, and liming showed minimal or negligible impact on SOC. Both CarboSeq and Beillouin et al. (2023) put high priority on biochar, a practice that has not been assessed in our project. However, the potential of biochar is very much depending on the availability of the biomass, for which there is strong competition (food, feed, materials, bioenergy, soil improver).

### *4.7.3 Barriers to the adoption of sequestration practices*

The implementation of agricultural mitigation practices aimed at enhancing carbon sequestration in arable land faces several barriers. These challenges can be categorised into economic, technical and structural barriers which often interact and compound each other.

- Economic barriers are often seen as a major obstacle to farmers' ability to implement new mitigation practices. The most significant economic challenges include the perceived operating (seeds, labour, new technology, soil testing, organic amendments) and capital investment (purchase of land, buildings, construction) costs, as well as the risks (production risks) and uncertainties associated with adopting new practices. In many areas, there is a lack of adequate financial incentives, subsidies, or market mechanisms to encourage the adoption of carbon sequestration practices. Additionally, a short land tenancy can inhibit the adoption of these mitigation strategies (Buckwell et al., 2022).

- Technical barriers, such as technical know-how, etc. can hinder farmers' ability to successfully implement new or innovative practices. Many agricultural practices need to be tailored to local conditions to maximise their effectiveness. Additionally, the success of carbon sequestration practices can vary, based on the conditions, creating a barrier due to a lack of localised information. Another technical barrier can be a lack of education and training – farm advisory services are expected to play a crucial role here by providing farmers with tailored knowledge to help them thrive (Buckwell et al., 2022).

- Structural barriers can constrain farmers within a specific agricultural system, making it challenging to adopt new practices. These barriers include


Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

technological dependencies (specialised farms with high yields and a narrower range of crops), data management issues (with the introduction of precision farming, farmers can lose the ability to make their own decisions and to repair their equipment), and the influence of stakeholders throughout the food chain, including providers, processors, buyers, and retailers. This often leads to a preference for established cultivation methods and crop varieties (Buckwell et al., 2022).

## 4.8. Insights

In a study by Lugato et al. (2015), a business-as-usual situation and three alternative management scenarios were simulated, and concluded that there is a realistic potential for mitigation, based on feasible policy-oriented scenarios, of 549-2,141 Mt $CO_2$-eq from 2013 to 2100, which corresponds to 6.3 - 24.6 Mt $CO_2$-eq per year. In the EJP Soil CarboSeq project for the similar practices this potential was estimated at 1801 Mt $CO_2$-eq. Only a part of this can be attributed to soil carbon sequestration, e.g. Roe et al. (2021) estimate a carbon sequestration potential of 67.5 Mt $CO_2$-eq per year for cropland, also at EU scale.

**Scientists** should take into account that there is a wealth of literature available to document case study estimates of the technical sequestration potentials for individual practices such as cover and catch crops, crop rotation, and reduced tillage in the case of arable lands, and optimising manure application. These estimates come from experimental conditions with controls. Research should continue to consolidate the technical sequestration potentials of groups of agricultural practices that are crucial for CF. Specifically, the focus should be on how the sequestration potentials are influenced by regional variables like soil type and climate across the EU.

The calculated estimates of sequestration potential refer to the technical potential for sequestering carbon in croplands that could be achieved by fully implementing all available sequestration practices. On the other hand, for **policy makers**, it is important to take into account the "realistic" or "achievable" potential that would take into consideration various barriers that may limit the adoption of sequestration practices, such as cost-effectiveness and social, cultural, farm-level, and political constraints. Predicting both the technical and realistic sequestration capacity of agricultural soils under climate-friendly management is highly challenging due to the multitude of possible scenarios resulting from the combination of agricultural practices, their potential areas of application, and their interactions with other socio-economic factors.

The detailed results, which are important for **farmers, end-users, and stakeholders**, are referred to in Figure 19. The Figure 19 indicates that zero tillage practice has the highest median carbon sequestration potential, while crop rotation practices show the lowest. It is crucial for farmers to recognise that CF involves a combination of multiple practices rather than relying on a single approach. Therefore, individual results should not be overvalued. For example, although zero tillage shows the highest median potential for carbon sequestration, the wide range of values reported across different studies



Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

introduces uncertainty. Conversely, the sequestration potential for catch and cover crops exhibits less variability, suggesting more consistent and reliable outcomes.

It can be concluded that zero tillage practice has the highest median of carbon sequestration potential, whereas crop rotations practices show the lowest. The detailed results can be found in the preceding sections. It is crucial to recognise that CF involves a combination of multiple practices rather than relying on a single approach. Therefore, individual results should not be overvalued. For instance, while zero tillage shows the highest median potential for carbon sequestration, the wide range of values reported across different studies introduces uncertainty. Conversely, the sequestration potential for catch and cover crops exhibits less variability, suggesting more consistent and reliable outcomes (Figure 20).

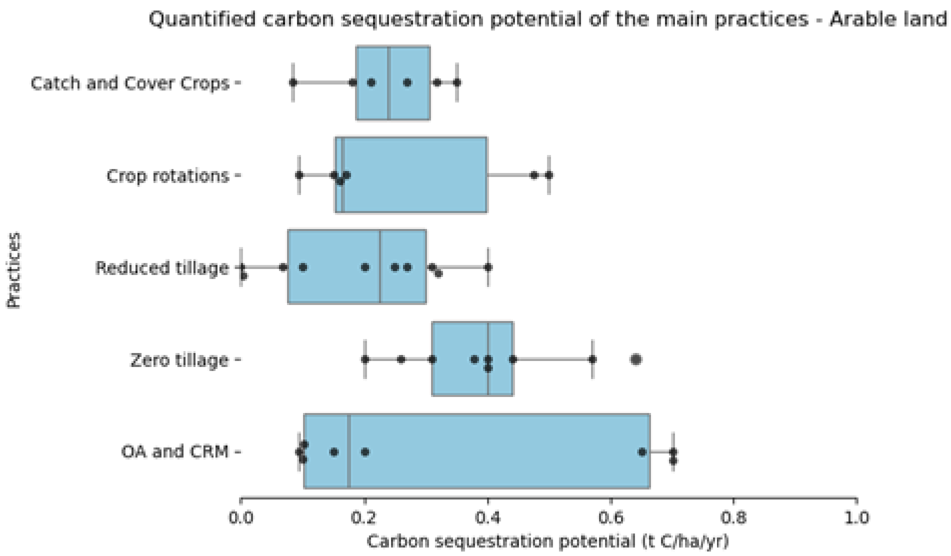



**Figure 19.** Quantified carbon sequestration potential of the main practices on the arable land. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# 5. Grasslands

Authors: Svoboda Adam[1], Torrús Castillo Milagros[2], Dankers Caroline[3], Holec Josef[1], Janků Jaroslava[1], Lesschen Jan Peter[3], Poláková Jana[1]

[1]*Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Science Prague (CZU), Czechia*

[2]*Spanish National Research Council (CSIC), Spain*

[3]*Wageningen Environmental Research, Wageningen University & Research, Wageningen, Netherlands.*

## 5.1. Methodology for information search

We performed a systematic search for peer-reviewed studies (meta-reviews, empirical and model studies) on SOC stock change using SCOPUS, Web of Science, and Google Scholar search engines in March and April 2024. Due to the limited number of studies dealing with carbon sequestration in grasslands, we extended our search beyond Europe, complementing it by empirical and model studies to fill the shortcomings in information provided by meta-reviews. The research queries were developed to include various agricultural practices, such as optimising manure application, maintenance of permanent grassland/pasture, optimising grazing intensity, grassland renewal, and improved manure processing on grassland and their potential to sequester carbon (grassland* AND "carbon sequestration*" AND "(selected agricultural practice)*"). This comprehensive approach aimed to capture a wide range of data and insights from existing literature.

We screened the full text of 24 studies (60 entries) from 6 different geographical zones published during the last 24 years for their potential inclusion in this study (Figure 20).

To ensure the quality and relevance of the studies included, we established several stringent criteria for selection. Specifically, a study had to:
a) Be published in English to ensure accessibility and comprehensibility.
b) Include a robust statistical analysis with a well-documented methodology to guarantee the reliability of the findings.
c) Investigate the impact of agricultural practices on SOC stocks, directly addressing our research objectives.
We retained 12 peer-reviewed studies (8 meta-reviews, one empirical study, two models and one book) containing four different practices: maintenance of permanent grassland/pasture, optimising manure application, optimising grazing intensity, and conversion from arable land to grassland.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

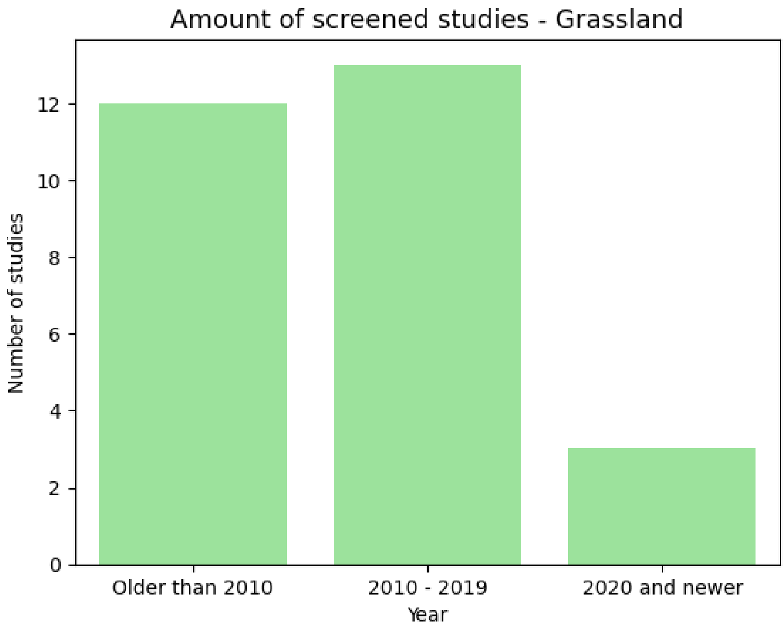



**Figure 20.** Number of grassland studies by year of publication.

The screening process was thorough and detailed, considering several critical factors: farmer practices, their impact on SOC, quantified carbon sequestration potential (expressed in appropriate units), control, sampling depth, duration of the study, and any additional notes deemed relevant.

## 5.2. Management considered

Maintenance of permanent grassland and pasture

Grassland in agriculture is regularly harvested. Harvesting can take various forms such as grazing, mowing (for fodder and energy purposes) or just cutting/mulching, where the biomass is crushed and left on the soil surface. These processes also maintain the character of the plant community. As grassland is not a climax-type community in most of Europe, the absence of management leads to successional processes, where desirable species disappear and higher herbaceous and then woody vegetation spreads. This reduces the productive importance of the habitat.

Regular maintenance of grasslands preserves their character. It allows the creation of a diverse plant and animal community that is resistant to disturbance. Degradation due to inappropriate management can lead to a decline in production and therefore a reduction in the amount of carbon stored in biomass. Long-term lack of management, on the other hand, leads to the development of woody plants that are capable of sequestering significant amounts of carbon in above – and below-ground biomass. This, however, removes the area from the agricultural production process.

Optimising manure application

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

By regular harvesting, a certain amount of nutrients is exported from the grassland, which cannot be fully replaced by natural processes in the short term. The amount of nutrients in the soil gradually decreases, leading to a shift in species composition towards less nutrient demanding and less productive species. By appropriate fertilisation, nutrients can be replenished and grassland production maintained or increased. Both liquid and solid fertilisers can be applied to grassland.

Appropriate fertilisation supports biomass production, both above and below the ground. The nutrients contained in the fertiliser are incorporated into plant biomass and the biomass of soil organisms. The total amount of SOM is thus increased. However, in the case of high doses of fertiliser, biodiversity is reduced, many of the more sensitive species gradually disappear and a few nitrophilous species dominate, which also harms the soil community.

Optimising grazing intensity

The grazing load, determined by the number of livestock units per unit area, significantly affects both the plant community and the soil at the site. Overgrazing gradually degrades the plant cover, reduces the above-ground biomass, which is not able to regenerate, and leads to soil compaction, higher animal excrement loads, loss of sensitive plant species and an increased risk of soil degradation.

Grazing has a selective effect in that the grazed stand is dominated by species that can tolerate repeated disturbance, reducing the amount of dead plant matter on the soil surface, and reducing the height but increasing the density of grazed vegetation. Appropriate stocking produces species-rich stands of plants to which a diverse community of other groups of organisms is linked. SOM is enriched by animal excrements, which are used by specialised coprophages. Balanced grazing by large herbivores is a key process of the world's grassland biomes to prevent their degradation.

Conversion from arable land to grassland

Arable land represents a more intensive form of agricultural land use. High productivity is achieved through the cultivation of annual crops and intensive agrotechniques. However, this also entails a higher risk of soil erosion and other forms of degradation. While the establishment of grassland on arable land reduces potential food production, it significantly increases the stability of the agroecosystem. Both meadows and pastures can be established on arable land. The practice should be, however limited spatially to zones fragile to erosion to avoid indirect land use change. Mixtures of forage-valuable grasses and clovers are usually used for sowing. The specific species are selected according to the soil and climatic conditions of the site.

By replacing annual crops with permanent grassland on arable land, year-round vegetation cover is achieved. The soil is not tilled, thus reducing the intensity of mineralisation of SOM. As a result of the continuous fall of dead plant parts and the dense root system of the grassland, a continuous supply of organic matter is ensured as a source of food for soil organisms. This, together with the absence of tillage and pesticide application, also promotes a higher biomass of the soil community.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

## 5.3. Variables used

The screening process was thorough and detailed, considering several critical factors: farmer practices, their impact on SOC, quantified carbon sequestration potential (expressed in appropriate units), control, sampling depth, duration of the study, and any additional notes deemed relevant.

During the systematic analysis of the published studies, the values and units of SOC reported by each study were recorded. The primary focus was on variables that provide quantifiable measures of carbon sequestration, which are essential for assessing the impact of different agricultural practices on SOC stocks. The recorded units were:

Annual SOC stock change rate (t C/ha/yr; t $CO_2$/ha/yr)
SOC concentration (%)

To create a coherent and unified analysis, it was necessary to convert all values to a common unit: tons of carbon per hectare per year (t C/ha/yr). This conversion was done for several reasons: i) Converting all values to a single unit allows for direct comparison across different studies and variables. It eliminates the disparity that arises from using different units of measurement and ensures that all data points are evaluated on the same scale,
ii) The used unit t C/ha/yr is highly relevant to agricultural studies as it provides a direct measure of how much carbon is sequestered per unit area over a given time, iii)The usage of common and well-known units simplifies the presentation of results, making it easier for stakeholders, policymakers, and researchers to understand, interpret and compare the findings and iv)Almost all carbon sequestration potentials from chosen studies were in t C/ha/yr. If the results were in units of t $CO_2$e/ha/yr, the following conversion was used:

1 ton of $CO_2$e emissions = 1 ton × 12/44 = 0.27 tons C emissions

## 5.4. Analysis

The selected studies provided comprehensive information on the observed impact of various agricultural practices on carbon sequestration. Descriptive statistics were employed to analyse the data. In cases where a range of values was reported, the mean value was utilised to ensure consistency and comparability across studies. For visual comparison and better interpretation of the results, the values were represented in graphical form using boxplots and scatter plots. These visualisations were created using the Python programming language, specifically employing the Seaborn library.

To effectively highlight the central tendency, variability, and the presence of outliers across different studies, box plots were used. The authors of these studies are provided in the legend for reference. The individual plots represent the lower quartile value (Q1) and the upper quartile value (Q3), with outliers denoting the minimum data value and maximum data value.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

The scatter plots were used to represent the data concerning the soil depth at which sampling was conducted. Studies were categorised based on these soil depths, while individual depths represent the studies, with the authors listed in the legend. The x-axis of the scatter plot indicates the various soil depths (e.g., 0-30 cm, NA – soil depth information not available), while the y-axis shows the carbon sequestration potential in t C ha$^{-1}$ year$^{-1}$. This visualisation allows a comparison of carbon storage across different depths, providing insights into how soil depth influences carbon storage. Additionally, the scatter plot can help identify patterns or trends that may not be immediately evident in tabular data.

## 5.5. Results

Figure 21 shows the sequestration potential of maintenance of permanent grassland as reported by selected studies. All studies were published before 2010 and positively impacted the annual SOC change rate with quantified potentials ranging from 0.175 to 0.59 t C/ha/yr. When maintaining permanent grassland, the management practices considered are improved grassland management, increased productivity by irrigation and introduced new species. All studies are considering non-European grasslands. Conant et al. (2001) provide values from Canada, the USA and Australia. Hutchinson et al. (2007) and Follett et al. (2001) provide values from North America. The median value is determined to be 0.23 t C/ha/yr. The study conducted by Conant et al. (2001) states that the median soil sampling depth was 15 cm.

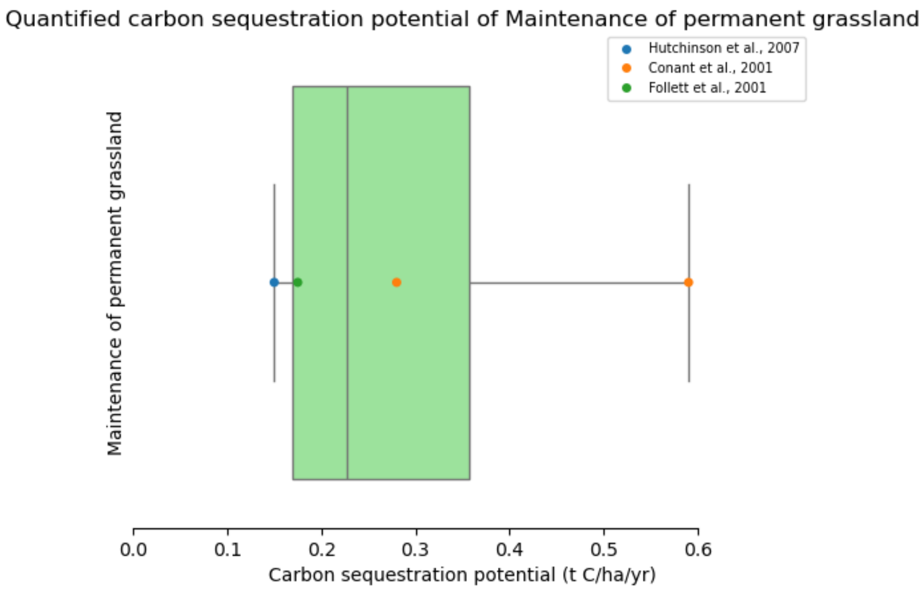



**Figure 21.** Quantified carbon sequestration potential of Maintenance of permanent grassland. References are provided in the legend. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

Figure 22 shows the sequestration potential of manure application optimisation reported by each study. Two studies were published before 2010 and the rest between 2011 and 2019. Not all studies confirm a positive impact on SOC content, for example empirical study by Cowie et al. (2013) showed no significant differences. However, studies with a positive impact on SOC quantified potentials ranging from 0.28 to 0.82 t

C/ha/yr. The lowest values of 0.28 t C/ha/yr have been reported by Conant et al. (2001). The median is set at 0.59 t C/ha/yr and the mean at 0.57 t C/ha/yr. Except for the Cowie et al. (2013) study, other studies are global and in the case of Whitehead et al. (2018) New Zealand.

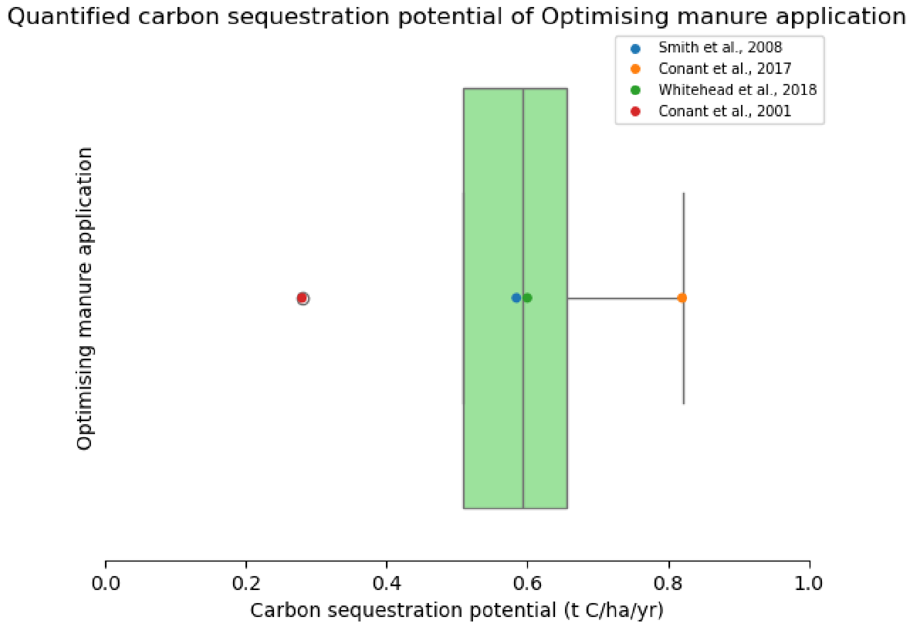



**Figure 22.** Quantified carbon sequestration potential of Optimising manure application. References are provided in the legend. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

Two studies, namely Conant et al. (2017) and Whitehead et al. (2018), reported information on soil sampling depth of 20 cm (Figure 23). For the 20 cm depth, the average value is 0.71 t C/ha/yr, whereas for the studies without the mentioned depth, the average value is set at 0.43 t C/ha/yr.

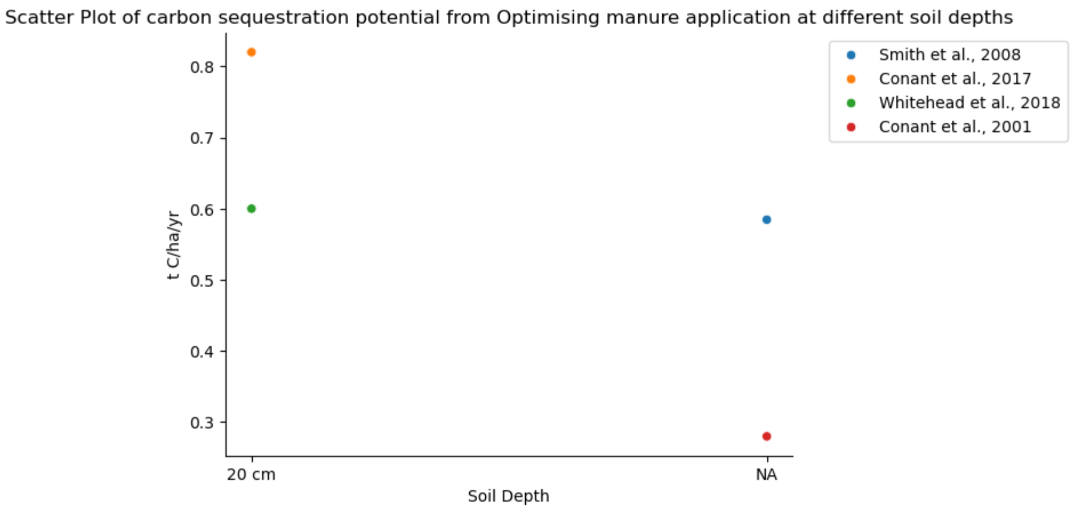



**Figure 23.** Carbon sequestration potential of Optimising manure application at different soil depths. The x-axis indicates the various soil depths (e.g., 0-30 cm, NA). The y-axis shows the carbon sequestration potential in t C/ha/year.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

The carbon sequestration potentials when optimising grazing intensity can be seen in Figure 24. Studies by Hutchinson et al. (2007) and Smith et al. (2008) report low values of 0.05 and 0.1242 t C/ha/yr, respectively, with low confidence and feasibility of the result, while studies by Conant et al. (2001) and Freibauer et al. (2004) report values in the range of 0.35–0.46 t C/ha/yr. Thus, the overall range of values is 0.05–0.46 t C/ha/yr, the median is set at 0.23 t C/ha/yr and the mean at 0.24 t C/ha/yr. All four studies do not provide information about soil sampling depth and have a global range.

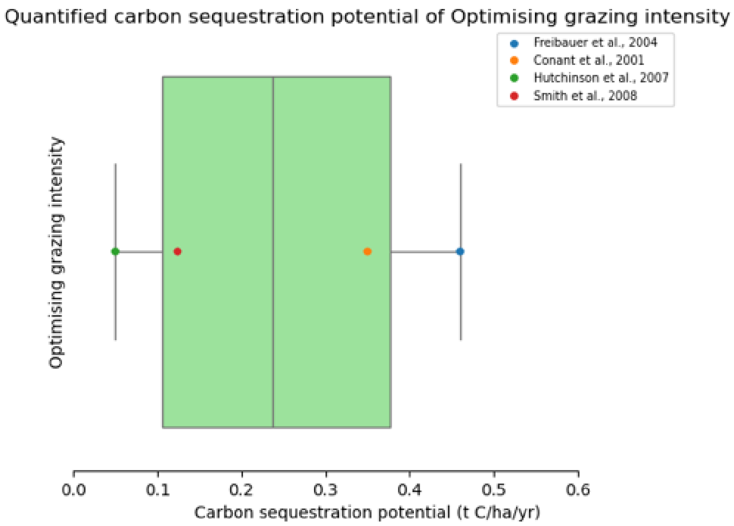



**Figure 24.** Quantified carbon sequestration potential of Optimising grazing intensity. References are provided in the legend. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

The results of five studies that met the criteria for inclusion requirements can be found in the figure below (Figure 25). Four studies are from before 2010, and two studies are from 2011–2019. Conversion from arable land to grassland is generally associated with positive impacts on SOC sequestration with, in this case, quantified potentials ranging from 0.45 to 1.9 t C/ha/yr. The lowest values come from authors Freibauer et al. (2004) (0.45 t C/ha/yr) and Minasny et al. (2017) (0.49 t C/ha/yr and 0.51 t C/ha/yr respectively). The highest sequestration value, 1.9 t C/ha/yr, is shown by Freibauer et al., 2004 in 0–30 cm soil depth. The median is set at 1.01 t C/ha/yr and the mean at 1.06 t C/ha/yr. All studies except Conant et al. (2001) (global) focus on Europe and the European Union. Two studies using a model to quantify carbon sequestration (Vleeshouwers & Verhagen, 2002; Lugato et al., 2015) reported different values. A study by Vleeshouwers & Verhagen reported value of 1.44 t C/ha/yr (above median), whereas a study by Lugato et al. reported value of 0.6 t C/ha/yr (below median).

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

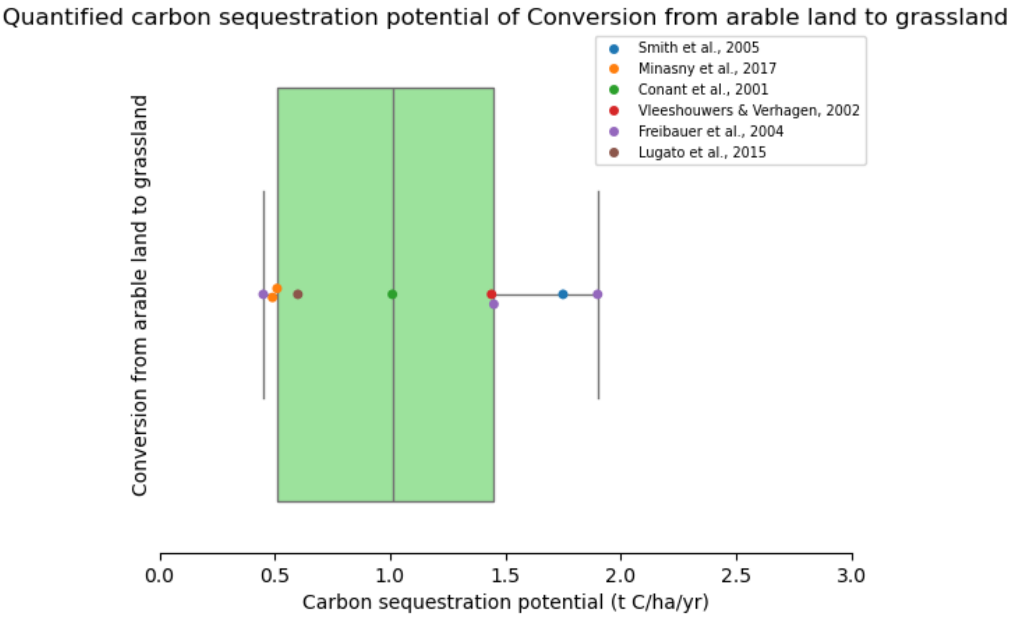



**Figure 25.** Quantified carbon sequestration potential of Conversion from arable land to grassland. References are provided in the legend. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

A scatter plot dividing the studies according to the soil sampling depth shows that the highest value of carbon sequestration, 1.44 t C/ha/yr, was recorded by Vleeshouwers & Verhagen (2002) at a depth of 30 cm. For depths 0–30 cm and 0–23 cm, the results were different (Figure 26). The median value for 0–30 cm was 0.6 t C/ha/yr (Lugato et al., 2015), and the mean value was 0.98 t C/ha/yr. Depth 0–23 cm had the lowest sequestration potential value (0.51 t C/ha/yr). Studies that did not report soil depth had both median and mean values of 1.38 t C/ha/yr.

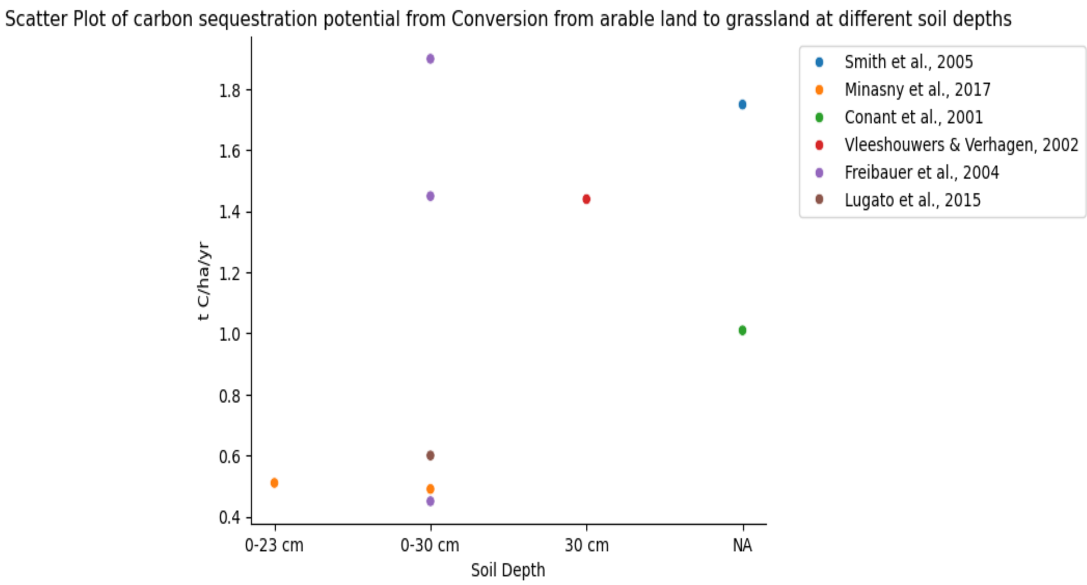



**Figure 26.** Carbon sequestration potential of conversion from arable land to grassland at different soil depths. The x-axis indicates the various soil depths (e.g., 0-30 cm, NA). The y-axis shows the carbon sequestration potential in t C/ha/year.

## 5.6. Co-benefits

Enhanced maintenance of permanent grassland/pasture may reduce nitrogen and phosphorus leaching and prevent soil erosion.

Optimising manure application can reduce nitrate leaching and increase SOM, leading to improved water retention and enhanced soil biodiversity. Additionally, manure serves as a natural source of nitrogen, potentially reducing the need for chemical nitrogen fertilisers. At the same time, applying manure to soil can help reduce soil erosion and nitrate leaching, while also providing benefits to biodiversity (Smith et al., 2008).

The benefits of restoring grassland habitats such as conversion from arable land can be substantial, depending on the end use and type of habitat restored. This restoration has the potential to reduce nutrient leaching and enhance biodiversity by fostering the development of species-rich grasslands (Freibauer et al., 2004).

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Summary of co-benefits of mitigation practices by agricultural systems

**Table 11.** Drivers affecting variability, adaptation, benefits, trade-offs effect on productivity and reference of the main management practices of grasslands.

| | Drivers affecting variability | Climate benefits – Adaptation | Benefits |
|---|---|---|---|
| **Optimising manure application** | Manure composition and quality combined with application rate, timing, soil characteristics and manure handling and storage. Interaction with other agricultural practices also plays a big role | Nitrate leaching reduction; increased SOM; water retention | Nitrate leaching reduction; manure application increases SOM in soils with beneficial impacts for water retention and soil biodiversity. It is also a source of N, which can replace chemical N fertiliser |
| **Maintenance of permanent grassland** | Environmental conditions, soil type, type of practices, grassland species composition, livestock management, external inputs and disturbances | Possible increase in water holding capacity. | Nitrogen and phosphorus leaching reduction, soil erosion prevention |
| **Optimising grazing intensity** | Grazing intensity, grassland species, composition, grazing strategy, duration of grazing | Depending on local conditions, grazing patterns may need to be adjusted to remain productive | Reduces soil erosion, reduces nitrate leaching, and benefits biodiversity |
| **Conversion from arable land to grassland** | Climatic condition, soil texture, site preparation and management, vegetation type, land use history, age since land-use conversion | Floods mitigation | Potentially high benefits depending on end use and type of restored grassland habitat. May reduce leaching; benefits to biodiversity by developing species-rich grasslands |
| | **Trade-offs** | **Effect on productivity** | **Reference** |
| **Optimising manure application** | Possible trade-offs with ammonia volatilisation and pollution transfer from air to soil. Possible significant transport fuel costs associated with moving manure and sludge over large | Positive | Frelih-Larsen et al., 2008; Smith et al., 2008 |

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

| | | | |
|---|---|---|---|
| | distances. Risk of increased pollution if the manure is not managed properly | | |
| **Maintenance of permanent grassland** | Not identified | Positive/negative | Conant et al., 2001; Smith et al., 2008 |
| **Optimising grazing intensity** | Higher use of energy for food and concentrates. Higher CH4 emissions from stored manure | Positive | Frelih-Larsen et al., 2008; Smith et al., 2008 |
| **Conversion from arable land to grassland** | Reduced agricultural productivity, profit loss | Negative – loss of production | Smith et al., 2008; Freibauer et al., 2004 |

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# 5.7. Discussion

Variability in reported carbon sequestration potentials arises from methodological differences, varying pedoclimatic conditions (Brombin et al., 2020), and experimental factors like sampling depth (Olson & Al-Kaisi, 20155) and sequestration duration (West & Six, 2007).

Different types of grasslands and pastures have varying capacities for carbon sequestration due to the species composition, management practices, and soil conditions (Conant et al., 2017). Carbon sequestration management can be also affected by variations in grazing management (Bai & Cotrufo, 2022), mowing, fertilisation practices and inconsistent management practices (Senapati et al., 2014). The carbon content and nutrient composition of manure vary depending on the source (Sharma et al., 2022). Variability in application practices, as well as how manure is stored and handled before application, can influence its carbon content and emissions (Petersen, 2017). Different grazing regimes can result in varying levels of carbon sequestration (Ding et al., 2024). Uncertainty can be also introduced by different types of forage, plant species (variability in plant composition) present in grassland (Skinner & Dell, 2016). The success of establishing and maintaining carbon sequestration on grassland after conversion from arable depends on factors such as plant species, management practices (post-conversion management practices including grazing, mowing, and fertilisation) (Ghosh & Mahanta, 2014), and soil properties (Balasubramanian et al., 2020). Carbon sequestration in grasslands also follows a saturation curve (gradual decline in annual sequestration) (Heikkinen et al., 2014). In principle, these types of conversion should be limited to soils fragile to erosion to avoid indirect land use change which can impact food production and supply (Smith et al., 2008).

For grasslands, Beillouin et al, (2023) ranked organic amendments as the most effective for SOC enhancement, followed by biochar. Grazing, particularly intensive grazing, often led to SOC declines, emphasizing the importance of organic inputs for SOC enhancement in grassland systems.

A meta-review of CF systems implemented by 12 private or public entities has shown that carbon removals in grassland soils are influenced by various factors such as administrative costs, monitoring methodologies, and the standardisation of offset verification. These factors vary depending on the types of practices implemented and the system providers (McDonald et al. 2021a; 2021b).

Soil scientists have highlighted the intermediate impact that sequestration practices have on the complex ecosystems of grassland soils, which include interactions between plants, fungi, and bacteria. The effectiveness of carbon sequestration in these environments depends on factors such as soil type, depth, rock fraction, and local climate. Given that carbon sequestration processes span years to decades, there is also the potential for carbon re-emission (Hepburn et al., 2019). Moreover, long-term changes in soil carbon content over thousands of years could potentially outweigh the short-term effects of current grassland management practices.

One of the most significant challenges in understanding carbon sequestration in grasslands and pastures is the lack of new long-term data, specifically long-term data from Europe. This is an important limitation in the analysis, given the climatic and edaphic differences between Europe and the world regions addressed in the reviewed studies. Furthermore, most studies focus on short-term effects, which may not fully capture the long-term impacts of various mitigation practices. This limitation is compounded by the wide variability in soil types and climate conditions across different grasslands, which can significantly influence carbon sequestration rates. This variability makes it difficult to generalise findings from one region to another, adding another layer of uncertainty.

Grazing intensity is known to play a crucial role in carbon sequestration, but the specific mechanisms and thresholds that govern its impact are still not well understood. Further research is needed to clarify how different grazing regimes, timing, and intensity levels affect soil carbon stocks over time. Similarly, the role of plant species composition and biodiversity in carbon sequestration remains an area where our knowledge is limited. Different plant species contribute varying amounts of carbon to the soil through their root structures and growth patterns, and understanding these dynamics is essential for optimizing carbon storage.

Socio-economic and policy factors further complicate the picture. Land ownership patterns, agricultural policies, and economic incentives can significantly influence the adoption and success of carbon sequestration practices. However, these influences are not well-documented, making it challenging to develop effective and widely applicable policies.

Monitoring and verifying carbon sequestration at scale also presents significant challenges. Accurate measurement of soil carbon changes is difficult, and existing techniques may not detect small but meaningful changes, complicating efforts to validate the effectiveness of mitigation practices. Lastly, the impact of climate change on carbon sequestration potential in grasslands and pastures is not fully understood. Variations in temperature, precipitation patterns, and extreme weather events can alter the carbon balance in unpredictable ways, making it even more difficult to forecast and manage carbon sequestration in these ecosystems effectively.

The implementation of agricultural mitigation practices aimed at enhancing carbon sequestration in grasslands faces several barriers. These challenges can be categorised into economic, technical and structural barriers which often interact and compound each other. The details on these barriers are the same as for arable lands – see section.

### 5.8. Insights

**Scientists** should take into account that there is a wealth of literature available to document case study estimates of the technical sequestration potentials for individual practices such as the conversion from arable land to grassland and optimising manure application. These estimates come from experimental conditions with controls.

Specifically, the focus should be on how the sequestration potentials are influenced by regional variables like soil type and climate across the EU.

The calculated estimates of sequestration potential refer to the technical potential for sequestering carbon in grasslands that could be achieved by fully implementing all available sequestration practices. On the other hand, for **policy makers**, it is important to take into account the "realistic" or "achievable" potential that would take into consideration various barriers that may limit the adoption of sequestration practices, such as cost-effectiveness and social, cultural, farm-level, and political constraints.

In Figure 27 it is indicated that conversion from arable land to grassland has the highest median carbon sequestration potential, while maintenance of permanent grassland shows the lowest. It is crucial for farmers to recognise that CF involves a combination of multiple practices rather than relying on a single approach.

Figure 27 shows that conversion from arable land to grassland practice has the highest median of carbon sequestration potential, whereas maintenance of permanent grassland shows the lowest. The detailed results can be found in the preceding sections. It is crucial to recognise that CF involves a combination of multiple practices rather than relying on a single approach. Therefore, individual results should not be overvalued. For instance, while conversion from arable land to grassland shows the highest median potential for carbon sequestration, this practice should be spatially limited to zones fragile to erosion so as to avoid indirect land use change. Further, the wide range of values reported across different studies introduces uncertainty.

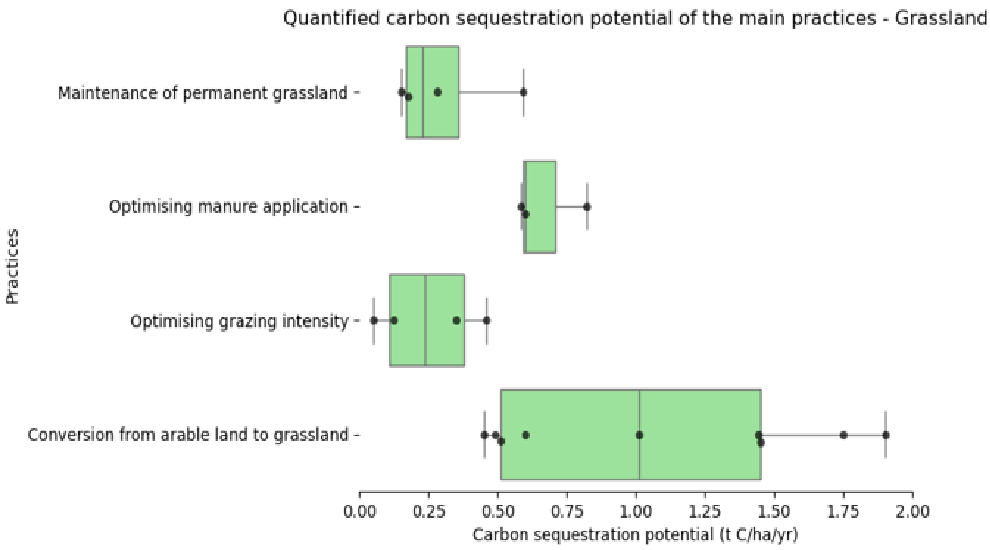



**Figure 27.** Quantified carbon sequestration potential of the main practices on the grassland. The lower quartile value (Q1) and the upper quartile value (Q3) with outliers denoting the minimum and maximum data values are shown.

# 6. Agroforestry

Elena Larysch[1], Milagros Torrús Castillo[3], Paul Pardon[2]

[1] *Chair of Forest Growth and Dendroecology, University of Freiburg, Germany*

[2] *Flanders research institute for agriculture, fisheries and food (ILVO), Belgium*

[3] *Spanish National Research Council (CSIC), Spain*

## 6.1. Methodology for information search

The literature review was conducted using Google Scholar as the primary search engine to identify relevant academic publications. The key terms used in the search included "agroforestry," "agro forestry," and "AFS," in combination with terms such as "soil carbon," "soil carbon sequestration," "carbon mitigation," "soil carbon stock," and "carbon mitigation potential." This combination of keywords was chosen to ensure a comprehensive coverage of the topic and to capture the various dimensions of soil carbon dynamics and mitigation potentials within agroforestry systems (AFS). The search resulted in articles published in the period from 2006 to 2022, including both meta-analyses and experimental studies. We identified 11 articles that aligned with the variables necessary for comparison, specifically the soil carbon sequestration rate in Europe. Of these 11 articles, 6 are empirical studies, while 5 are meta-analyses. All the articles are published in peer-reviewed journals. Using the results from the meta-analyses in detail, we could gain insights into 327 studies on soil carbon sequestration potential in AFS. To structure the review, AFS were categorised into two main types: silvoarable (integrating trees with crops) and silvopastoral (integrating trees with livestock grazing systems). This division allowed for a detailed examination of the distinct impacts of each system on soil carbon stocks. The review focused on evaluating the impact of these systems on SOC stock and the rate of SOC sequestration (expressed as C $ha^{-1}$ $yr^{-1}$).

## 6.2. Management considered

Agroforestry systems (AFS) are multifunctional land-use practices that integrate woody perennials like trees and shrubs with agricultural activities. These systems are primarily classified into two types based on the nature of the agricultural component: silvoarable and silvopastoral.

Silvoarable systems combine woody crops with agricultural crops. In these systems, trees and crops coexist on the same land, offering a synergistic relationship where both components benefit from each other. The trees in silvoarable systems contribute to soil fertility through nutrient cycling, enhance water retention, and provide shade, which can reduce the temperature stress on crops. These systems are particularly effective in regions where soil conservation is critical, as the presence of trees helps to reduce wind erosion and improve overall land productivity.

Silvopastoral systems integrate woody plants with livestock grazing. In this setup, trees are combined with pasturelands where livestock graze. The trees provide multiple benefits to the livestock, including shade, which reduces heat stress, and shelter from wind and harsh weather conditions. Additionally, the organic matter from leaf litter and tree roots improves soil fertility, which can enhance pasture quality and productivity. Silvopastoral systems are often found in regions where the combination of livestock and trees can lead to more sustainable land use, promoting both animal welfare and environmental health.

Woody component of agroforestry systems

In both silvoarable and silvopastoral systems, the woody component plays a crucial role. The arrangement and type of woody vegetation can vary significantly, but they generally fall into the following categories: trees and hedges.

In alley cropping systems, trees are planted in linear rows with crops grown in the spaces between them. This arrangement is common in silvoarable systems, where the rows of trees help to break the wind, reduce wind erosion, and provide a microclimate that is beneficial for crop growth. Moreover, trees help improve soil structure, increase organic matter content, and enhance water retention. In orchard systems, trees could also be planted in organised orchards or scattered throughout the agricultural land. These trees can provide fruits, nuts, or timber while also offering shade and contributing to soil health through organic matter inputs. Hedges are rows of closely planted shrubs or small trees that can serve multiple purposes. In agroforestry, they often act as natural boundaries or windbreaks. Hedges can also reduce soil erosion, provide habitats for wildlife, and in some cases, serve as a source of fodder for livestock. They are important in silvopastoral systems, where they can separate grazing areas or provide shelter for animals.

The woody component generally contributes to biodiversity by providing habitats for various species, and sequestering carbon, which helps mitigate climate change. These environmental benefits are particularly important in the context of modern agriculture, where soil degradation, loss of biodiversity, and climate change are pressing concerns.

Agricultural component of agroforestry systems

Besides the woody component, AFS involve the agricultural component, which can either be plant cultivation (in silvoarable systems) or livestock management (in silvopastoral systems). In this report, the primary focus is on silvoarable systems. The agricultural component in this system consists of crops grown alongside or between the woody components. The types of crops that can be cultivated vary widely depending on the climate, soil type, and overall objectives of the land use. Key considerations include either annual crops, perennial crops or intercropping.

Annual crops include cereals (such as wheat, maize, or barley), legumes (such as beans, peas, or lentils), and vegetables (such as tomatoes, potatoes, or leafy greens). The integration of trees with these crops can enhance yields by improving soil moisture retention and providing a more favourable microclimate.

Perennial crops, such as certain types of herbs, berries, or even certain types of grains (e.g. perennial wheat), can be grown in a silvoarable system. These crops benefit from the consistent soil cover provided by the trees, which reduces soil erosion and enhances


Project MARVIC has received funding from the Horizon Europe
Programme under grant agreement no. 101112942

nutrient cycling. Intercropping is a common practice in silvoarable systems, where multiple crops are grown together within the same field. This can include a mix of annuals and perennials or even different species that complement each other. The presence of trees in this system can help reduce competition between crops for sunlight, water, and nutrients.

By focusing on silvoarable systems, this report addresses the need for sustainable intensification of agriculture, where productivity is increased without compromising environmental integrity.

## 6.3. Variables used

In reviewing the carbon mitigation potential of AFS with a focus on soils, several key variables are crucial to take into account. The soil carbon sequestration rate, typically measured in tons of carbon per hectare per year (t C $ha^{-1}$ $yr^{-1}$), serves as the primary metric for assessing the effectiveness of these systems in capturing and storing carbon. To understand the distribution of carbon within the soil, it is essential to consider different soil layers, as carbon sequestration can vary significantly with depth. The type of AFS—whether silvoarable or silvopastoral—also plays a critical role in determining the overall carbon sequestration potential. Within the silvoarable system, a further distinction between alley cropping and hedgerows must be made, as these subtypes involve different management practices and structural arrangements, leading to varying impacts on soil carbon storage. By examining these variables, we can gain a more comprehensive understanding of the soil-related carbon mitigation benefits of different AFS approaches.

## 6.4. Analysis

Trees in silvoarable systems capture and store carbon dioxide from the atmosphere, contributing to climate change mitigation. The woody biomass and SOM in these systems can store significant amounts of carbon over time. Trees can modify the microclimate in agricultural fields by reducing temperatures, lowering wind speeds, and increasing humidity. This can create a more favourable environment for crop growth and reduce the impacts of extreme weather events. Nevertheless, if the management of silvoarable systems involves heavy machinery, there could be emissions related to fuel use and soil disturbance. Additionally, the initial establishment of such systems may involve clearing existing vegetation, potentially releasing stored carbon.

We evaluated soil carbon sequestration rates across different AFS, beginning with a comparison between silvoarable and silvopastoral systems. These two systems are the most implemented and are considered the foundational elements of agroforestry. Following this, we conducted an in-depth analysis of the silvoarable system, focusing on a comparison between the woody components that included trees in alley cropping systems and hedges. In both systems, cropland is integrated as a secondary practice. Given the distinct management practices required for trees and hedges, it is essential to assess the benefits of these silvoarable options in terms of soil carbon sequestration.

## 6.5. Co-benefits

Soil health and fertility: The roots of trees and shrubs in silvoarable systems help to stabilise the soil, reduce erosion, and improve soil structure. This can lead to better water infiltration and retention, reducing the need for irrigation. Trees contribute to nutrient cycling through leaf litter and root decay, which enrich the soil with organic matter and nutrients. This can reduce the need for chemical fertilisers, which are often associated with soil degradation and pollution. The presence of trees in silvoarable systems significantly reduces wind and water erosion. The root systems of trees help to bind the soil, preventing it from being washed away during heavy rains or blown away by strong winds. If not managed properly, trees and crops may compete for nutrients, water, and light. This competition can sometimes lead to reduced crop yields, especially if the tree species are not well-matched to the crops or if they are planted too densely.

Water management: The increased organic matter from tree litter and root systems improves the soil's ability to retain water, making the system more resilient to drought conditions. Trees can reduce surface runoff by improving soil structure and water infiltration. This helps to minimise the risk of flooding and soil erosion, particularly in sloped areas. Trees in silvoarable systems can potentially draw large amounts of water, which may reduce the availability of water for crops, especially in water-scarce regions. Careful species selection and management are required to mitigate this risk.

Biodiversity enhancement: Silvoarable systems can enhance biodiversity by providing habitats for a wide range of species, including birds, insects, and other wildlife. The diversity of plant species in these systems can also lead to increased microbial and invertebrate diversity in the soil. Trees and shrubs can attract pollinators and natural predators of pests, which can enhance crop pollination and reduce the need for chemical pesticides. This contributes to more sustainable agricultural practices. If non-native tree species are introduced into a silvoarable system, there is a risk that they could become invasive, outcompeting local flora and fauna and disrupting local ecosystems.

Air quality improvement: Trees act as natural filters for dust and particulates, improving air quality around agricultural fields. This is particularly beneficial in regions prone to wind erosion or those close to urban areas where air quality is a concern. By sequestering carbon and reducing the need for chemical inputs, silvoarable systems can contribute to lower GHG emissions compared to conventional agriculture.

Land use efficiency: Silvoarable systems make efficient use of land by allowing the simultaneous growth of trees and crops. This can increase overall land productivity and support food security while maintaining ecological balance.

## 6.6. Results

The following results demonstrate varying degrees of carbon mitigation potential across different AFS, highlighting their distinct contributions to climate change mitigation. First, we analysed the differences of soil carbon sequestration rates between the silvoarable and silvopastoral AFS (Figure 28).

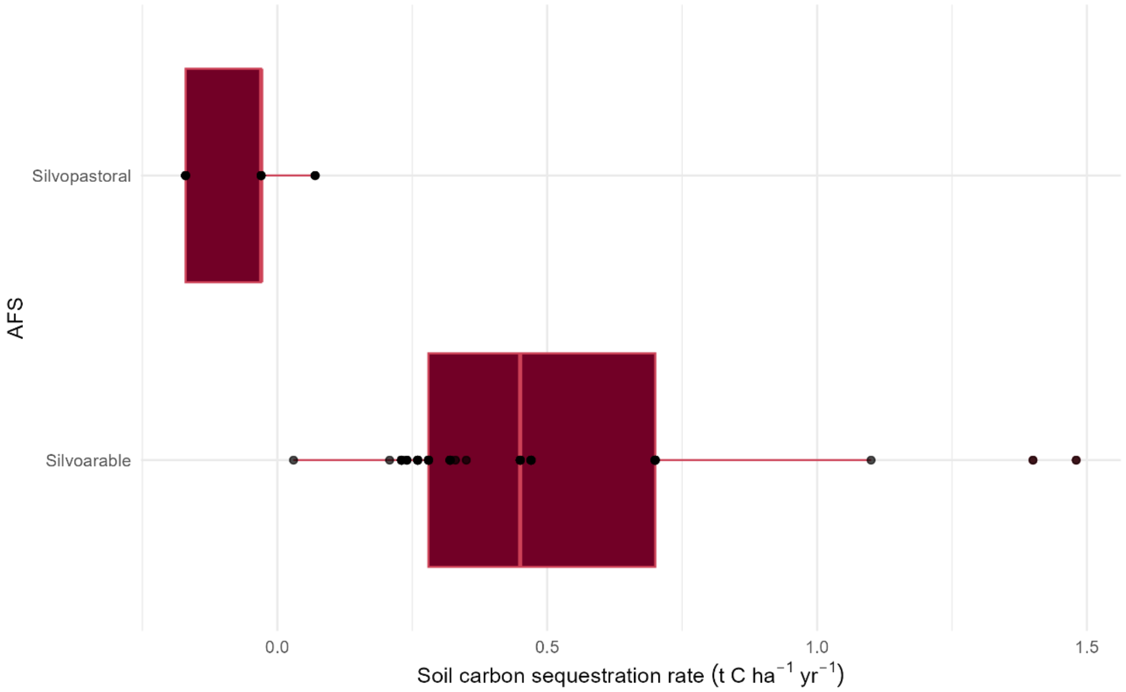



**Figure 28.** Soil carbon sequestration rate of soil layers from 0cm to 200cm, separately for the type of agroforestry system (AFS).

The soil carbon sequestration rates in the silvopastoral system are clustered around zero, indicating that the soil carbon sequestration rates for silvopastoral systems are generally low with a slightly negative rates reported in two studies.. Also, the range of values is very narrow, suggesting consistent but minimal carbon sequestration across the observed silvopastoral systems. The data points of the silvoarable system for silvoarable systems show a wider distribution, suggesting greater variability in the soil carbon sequestration rates. The interquartile range (represented by the red box) spans a larger section, indicating that these systems can potentially sequester more carbon compared to silvopastoral systems, but with a higher degree of variability. There are outliers extending beyond 1 t C $ha^{-1}$ $yr^{-1}$, though most data points cluster in the interquartile range of 0.28 and 0.70 t C $ha^{-1}$ $yr^{-1}$. This indicates that silvoarable systems generally have a positive and higher potential for soil carbon sequestration compared to silvopastoral systems, albeit with greater variability. This suggests that while silvoarable systems might offer more significant carbon sequestration benefits, their effectiveness can vary widely depending on specific conditions or management practices.

The soil carbon sequestration rates (in t C $ha^{-1}$ $yr^{-1}$) of two specific silvoarable practices within AFS, namely hedgerow and alley cropping, are depicted in Figure 29. Here, each data point corresponds to a value reported in articles (indicated by the colours representing different articles). In the hedgerow systems, the data points are spread across a wide range from just above 0 to over 1.5 t C $ha^{-1}$ $yr^{-1}$. The interquartile range (represented by the large red box) suggests significant variability in sequestration rates across different studies, indicating that hedgerow systems can offer substantial carbon sequestration potential under certain conditions. The majority of data points fall within the range of approximately 0.25 to 0.75 t C $ha^{-1}$ $yr^{-1}$, with a few outliers showing even

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

higher sequestration rates. The alley cropping systems show less variability compared to hedgerow systems, as indicated by a narrower interquartile range. The sequestration rates for alley cropping are generally lower, clustering around 0 to 0.5 t C $ha^{-1}$ $yr^{-1}$. Here, the variability among studies is less pronounced, suggesting that while alley cropping might be more consistent, it generally sequesters less carbon compared to hedgerow systems.

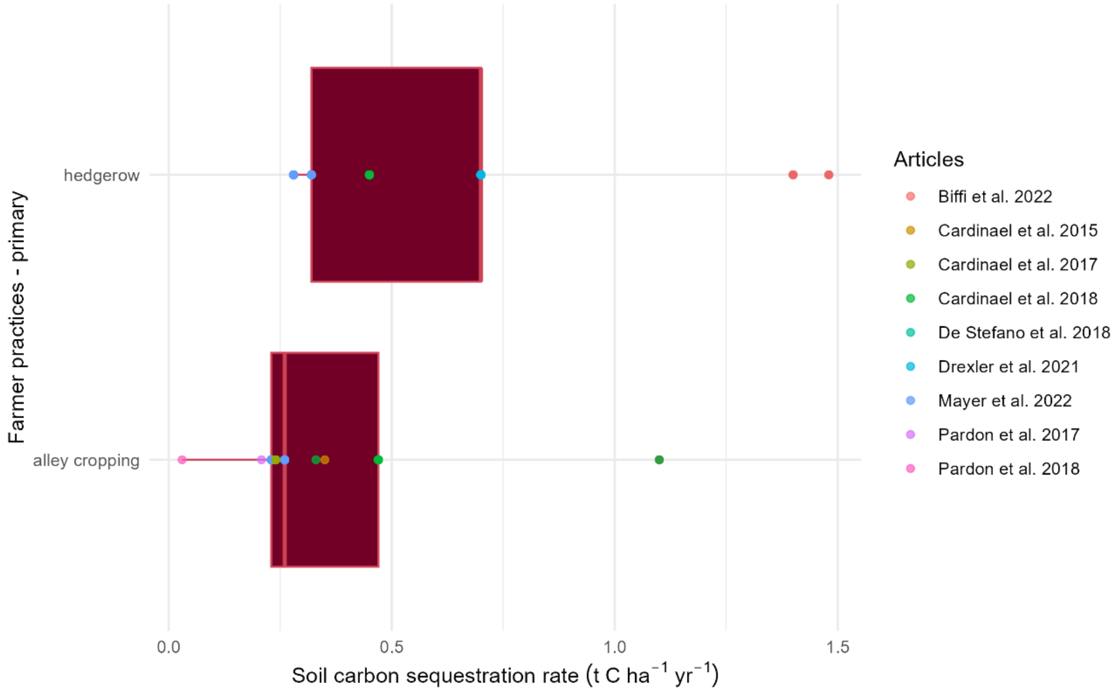



**Figure 29.** Soil carbon sequestration rate of silvoarable agroforestry systems.

The hedgerow systems tend to have a higher and more variable soil carbon sequestration potential compared to alley cropping systems within silvoarable practices. This variability in hedgerow systems suggests that they could be optimised for greater carbon sequestration under the right conditions, whereas alley cropping provides more consistent but typically lower sequestration rates. This highlights the importance of choosing the appropriate practice based on specific goals and environmental conditions when aiming to maximise soil carbon sequestration in agricultural systems. Figure 30 illustrates the different soil carbon sequestration rates by soil depth found in the literature search.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

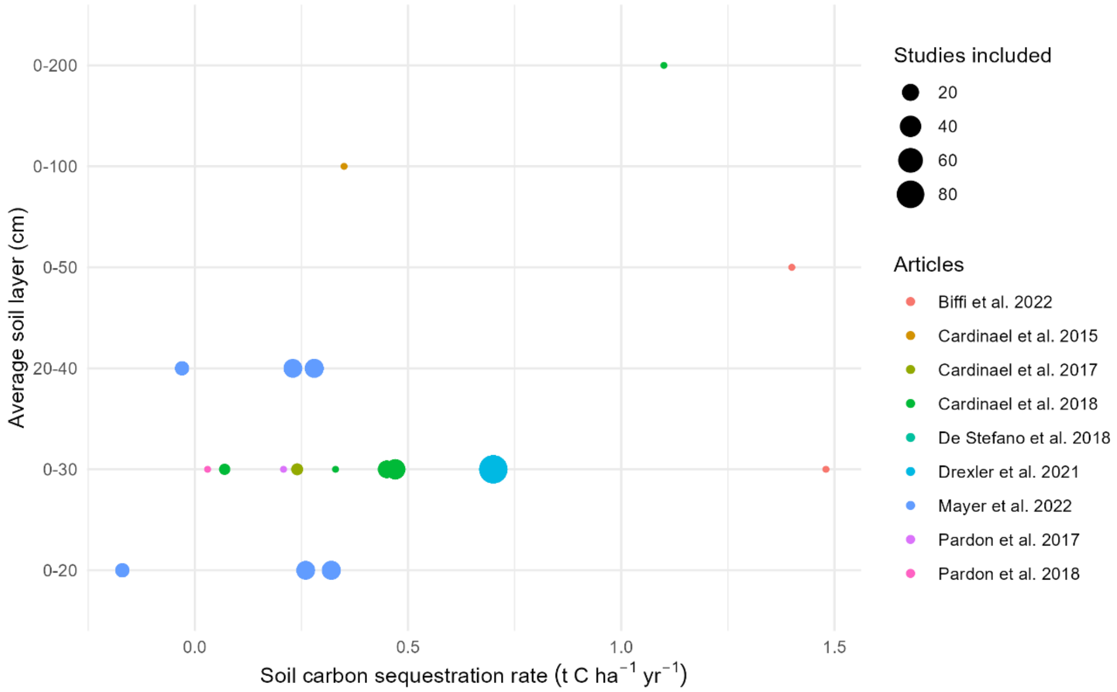



**Figure 30.** Soil carbon sequestration rates in silvoarable agroforestry systems across observed soil layers. The used studies are depicted in the size of the points.

## 6.7. Discussion

The available experimental information on carbon sequestration in AFS is subject to several sources of uncertainty. One significant challenge is the lack of data on bulk density, a critical factor needed to accurately convert soil carbon concentration into carbon stock, which is often unavailable or inconsistently reported. Additionally, variations in system age and tree age introduce further uncertainty, as the rates of carbon sequestration can differ significantly depending on the developmental stage of the system and the trees within it. These age-related differences can complicate comparisons across studies and systems. Tree density is another variable that is frequently underreported or not included in studies, despite its importance in influencing both aboveground and belowground carbon storage. The absence of this information can lead to a bias in the estimation of carbon sequestration potentials, contributing to overall uncertainty in the experimental data.

Nair (2012) already mentioned, that measuring and verifying carbon sequestration within AFS, is a difficult task and oftentimes, not enough data is available to retrieve reliable estimates on the realistic carbon sequestration potentials of AFS. To evaluate changes in SOC stocks and the resulting gains or losses following a land-use change, several fundamental input variables are necessary to know: the former land use, SOC stocks or SOC content together with bulk densities for both the prior and current land uses, the soil depth considered, and the time elapsed since the land-use change.

Climate is a fundamental factor that influences soil carbon dynamics, impacting key processes such as organic matter decomposition and root activity, which are central to soil carbon sequestration. Variability in climate, including fluctuations in temperature, precipitation, and seasonal patterns, can lead to inconsistent sequestration rates. In

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

regions with extreme or erratic climate conditions—such as areas prone to droughts, floods, or temperature extremes—the stability of soil carbon stocks can be unpredictable, complicating the task of making accurate long-term predictions. Additionally, the ongoing changes brought about by global climate change add another layer of uncertainty, as they may alter these conditions in unforeseen ways, affecting the future potential for carbon sequestration.

Temperature is a key driver of tree growth, directly affecting processes like photosynthesis, respiration, and biomass accumulation. In regions where temperature is a limiting factor, an increase in warmth can enhance tree growth and potentially boost carbon sequestration. However, there is a delicate balance; excessive temperatures can stress trees, reduce growth, or increase mortality, negatively impacting carbon storage. Additionally, temperature fluctuations influence soil microbial activity, affecting the breakdown of organic matter and the stabilisation of carbon within the soil. This temperature dependency introduces variability in sequestration rates, particularly across different geographic regions and climatic zones.

The combined effects of climate variability, tree species suitability, and temperature-driven growth create significant uncertainties in estimating the carbon mitigation potential of AFS. The complex interactions among these factors make it challenging to predict how AFS will perform in terms of carbon sequestration over time. Accurate, long-term estimates require localised, species-specific studies and adaptive management practices that can respond to changing environmental conditions. This approach is essential for optimizing carbon sequestration outcomes and effectively mitigating climate change through agroforestry.

In relation to general statements on the impact of management on carbon sequestration, silvoarable agroforestry, which combines trees or hedges and arable crops on the same land, has been proposed as a sustainable agricultural practice with significant potential for enhancing soil carbon (SOC) sequestration. Some of the reasons are as follows: AFS, including silvoarable, generally increase SOC stocks compared to conventional agricultural systems. This increase is observed across various soil depths and agroforestry practices (see Figure 28, 29 and 30) as well as in multiple peer-reviewed studies (Abbas et al. 2017, Mutuo et al. 2004, Palma et al. 2007, Shi et al 2018, De Stefano et al. 2017, Visscher et al. 2023). Transitioning from traditional agriculture to agroforestry significantly enhances SOC stocks. For instance, SOC stocks increased by 26% to 40% at different soil depths when land use changed from agriculture to agroforestry (Baah- Acheamfour et al. 2014, Palma et al. 2007, Peichl et al. 2006, De Stefano et al. 2017). The highest SOC sequestration rates are often found in the topsoil (0-20 cm or 0-30 cm), but significant increases are also observed in subsoil layers (20-100 cm). The effectiveness of silvoarable systems in sequestering carbon can vary based on regional climate, soil type, and precipitation. For example, silvoarable systems show greater benefits in arid or tropical climates with sandy soils and lower precipitation (Visscher et al. 2023). Silvoarable agroforestry has the potential to sequester substantial amounts of carbon over long periods. For instance, it can increase carbon sequestration by up to 140 tonnes C $ha^{-1}$ over 60 years (Lopéz-Diaz et al. 2017, Palma et al. 2007). Beyond carbon sequestration, silvoarable systems also contribute to other ecosystem services such as erosion control, nutrient provision, and increased biodiversity, which


Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

further support soil carbon stability (Abbas et al. 2017, Palma et al. 2007, Shi et al. 2018, Visscher et al. 2023).

Silvoarable agroforestry management significantly enhances soil carbon sequestration compared to conventional agricultural practices. This increase in soil carbon stocks is observed across various soil depths and is influenced by regional climate and soil conditions. Additionally, silvoarable systems provide multiple ecosystem services that contribute to the overall stability and sustainability of agricultural landscapes. Implementing silvoarable agroforestry on a larger scale could play a crucial role in mitigating climate change by sequestering atmospheric carbon dioxide in soils.

To address the gaps in knowledge that limit the quantification and prediction of the impact of mitigation practices on carbon sequestration in AFS, it's important to consider several key areas:

- Lack of a unified definition of AFS: The term "Agroforestry Systems" is not universally defined, leading to inconsistent data and confusion in research. This lack of a clear definition means that studies may not be directly comparable, as different systems may be classified under the same umbrella but have vastly different practices and impacts. Recommendation: Develop a standardised global framework for defining AFS that includes various sub-categories and practices, ensuring consistency in classification and reporting.

- Absence of a clear framework for assessment: There is no universally accepted framework for assessing the impact of AFS on carbon sequestration. Without a standardised assessment framework, comparisons across studies are difficult, and the effectiveness of different practices can be challenging to evaluate. Recommendation: Establish a comprehensive framework that includes key metrics and methodologies for evaluating carbon sequestration in AFS. This framework should consider both aboveground and belowground carbon stocks, as well as temporal and spatial variations.

- High system diversity: The diversity of AFS systems complicates the prediction of carbon sequestration outcomes. Variability in tree species, management practices, and environmental conditions leads to a wide range of sequestration outcomes, making it hard to generalise results. Recommendation: Conduct research that accounts for system diversity by including a range of tree species, management practices, and environmental conditions. Develop models that can accommodate and predict outcomes for different types of AFS.

- Variability in tree species and management practices: Different tree species and management practices affect carbon sequestration through varying root structures, litter fall, and overall growth dynamics. The variability in how tree species influence soil carbon sequestration complicates predictions and quantifications of their impact. Recommendation: Investigate the specific impacts of different tree species and management practices on soil carbon sequestration. Use this data to refine models that predict carbon sequestration based on species and management practices.

- Inconsistent research designs: Research designs widely, making it difficult to compare results. Diverse methodologies can lead to inconsistent results and hinder the ability to draw general conclusions. Recommendation: Promote the use of standardised research designs and modeling approaches. Encourage meta-analyses that use consistent methods to aggregate data and draw more reliable conclusions.

- Limitations of meta-analyses: Meta-analyses often average out results from studies with highly variable designs, which can obscure important nuances. Averaging can mask significant differences between studies and lead to oversimplified conclusions about carbon sequestration. Recommendation: Conduct meta-analyses with careful consideration of study design differences. Where possible, use advanced statistical techniques to account for variability and provide a more nuanced understanding of carbon sequestration.

By addressing these gaps, researchers and policymakers can develop more accurate models and strategies for predicting and enhancing the carbon sequestration potential of AFS.

Integrating trees into agricultural landscapes offers numerous environmental benefits, such as enhanced biodiversity, improved soil health, and increased carbon sequestration. Trees can provide shade, reduce soil erosion, and improve water retention, creating a more resilient and sustainable farming system. Moreover, AFS can contribute to long-term soil fertility by adding organic matter and fostering beneficial microorganisms, which can lead to more stable agricultural production over time. However, the inclusion of trees in these areas also comes with trade-offs. One of the primary concerns is the reduction in the area available for conventional agricultural activities. The land occupied by trees is no longer directly available for crop cultivation, leading to a potential decrease in yield per unit area. This reduction, known as agricultural extensification, can pose significant challenges, especially in regions where land availability is already limited or where food production must meet growing demands. The decrease in yield on existing farmland may drive farmers to compensate by expanding agricultural activities into previously untouched or pristine areas, such as forests, wetlands, or grasslands. This expansion could lead to deforestation, habitat destruction, and the loss of biodiversity, ultimately undermining the environmental benefits that agroforestry aims to provide. The conversion of these natural ecosystems into agricultural land also releases large amounts of stored carbon, contributing to climate change. Thus, while agroforestry presents a sustainable alternative to conventional farming, careful consideration must be given to its implementation. Strategies such as selecting optimal tree species, balancing tree density, and integrating crop systems that complement tree growth can help minimise yield losses. Additionally, policies that protect pristine areas and promote sustainable land management practices are essential to prevent the unintended consequence of increased pressure on these valuable ecosystems. Balancing the benefits of agroforestry with the need to maintain agricultural productivity and protect natural landscapes is crucial for achieving both food security and environmental sustainability. The effectiveness of an agroforestry system in sequestering carbon is heavily dependent on the choice of tree species, which must be well-suited to the local environment. Tree species differ significantly in their growth rates, root structures, biomass production, and the quality of litter they produce—all of which directly influence the amount of carbon that can be stored in the soil. When tree species are well-matched to the local climate, soil, and ecosystem, they can thrive, leading to higher carbon sequestration rates. Conversely, species that are poorly adapted may suffer from reduced growth or higher mortality rates, leading to less efficient carbon storage and increased uncertainty in carbon mitigation estimates.

Summary of co-benefits of mitigation practices by agricultural systems

Overall impact of these co-benefits with particular mention to uncertainty of the effects, and variability among farms, regions.

SOC sequestration. Practicing AFS, particularly silvoarable systems, can lead to an increase in SOC. Trees in these systems contribute organic matter to the soil through leaf litter, root turnover, and decomposition processes, which enrich the soil carbon pool. The rate at which SOC is sequestered varies depending on several factors, including the climate, the specific type of agroforestry system, the age of the trees, and the type of soil. For instance, in silvoarable systems, trees with high or exponential growth rates can enhance carbon sequestration during their early years, as they accumulate biomass rapidly, leading to higher carbon inputs into the soil.

Climate mitigation through carbon sequestration of trees. Trees in silvoarable systems not only contribute to SOC but also directly sequester atmospheric carbon dioxide through their growth. During the initial years, trees with high growth rates can sequester significant amounts of carbon, which helps in mitigating climate change. This carbon sequestration is an essential function of silvoarable systems, making them a vital tool in climate-smart agriculture.

Windbreaks and microclimate regulation. The trees in silvoarable systems can act as windbreaks, reducing wind speed across agricultural fields. This reduction in wind speed is beneficial as it lowers evapotranspiration rates from crops, thereby decreasing the water requirements of the crops. This is particularly advantageous in regions prone to drought or where water resources are limited.

Crop Yield Considerations. While trees provide numerous benefits, they also cast shadows that can impact crop yields. Tree shadows reduce the amount of sunlight reaching the crops, which may lead to lower photosynthesis rates and, consequently, reduced crop yields. Therefore, in silvoarable systems, the orientation of tree rows is a critical factor that must be carefully planned to minimise shading effects on crops. Proper alignment of tree rows can optimise sunlight exposure for crops while maintaining the benefits provided by the trees.

Silvoarable systems require a careful balance between maximizing environmental benefits and minimizing potential drawbacks. While the integration of trees improves soil health, sequesters carbon, and reduces water needs through windbreaks, careful management is essential to ensure that these benefits do not come at the cost of reduced crop yields due to shading.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

**Table 12.** Drivers affecting variability, adaptation, benefits, trade-offs effect on productivity and reference of the main management practices of agroforestry.

| Silvoarable | Drivers affecting variability | Adaptation | Benefits | Trade-offs | Effect on productivity | Reference |
|---|---|---|---|---|---|---|
| **Alley cropping** | Climatic factors<br>soil properties<br>agronomic practices<br>tree species selection<br>tree management (pruning)<br>root pruning<br>litter collection | soil structure<br><br>water infiltration<br><br>water holding capacity<br><br>wind reduction | Climate change mitigation via carbon stock in trees, SOC sequestration, higher soil health, reduced runoff and soil erosion, increased nutrient availability, benefits to biodiversity and water retention, less pesticides needed, additional income by selling timber or NT products like fruits or nuts. | Reduced crop yield (space and shade) | If high tree density per hectare, a extensification takes place, thus the yield will be reduced and pressure on land is increased | Staton et al. 2022, De Stefano and Jacobson 2017, Udawatta et al. 2019 |
| **Hedges** | Climatic factors<br>soil properties<br>agronomic practices<br>Hedge species selection<br>Hedge management (pruning)<br>root pruning<br>litter collection | soil structure<br><br>water infiltration<br><br>water holding capacity<br><br>wind reduction | SOC sequestration, Climate change mitigation via carbon stock in hedges, Wind break, higher soil health, reduced runoff and soil erosion, increased nutrient availability, benefits to biodiversity and water retention, less pesticides needed | On water limited sites: possible less available water for adjacent crops | Through reduced wind speed, evapotranspiration of crops will be reduced and crop yield could be increased | Staton et al. 2022, De Stefano and Jacobson 2017, Udawatta et al. 2019 |

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

## 6.8. Insights

**Scientists**: There are methodological challenges, such as estimating carbon stocks in biomass and soil under varying conditions is complex and often lacks rigor (Nair et al. 2009, Makundi et Sathaye 2004, Lorenz et Lal 2014). The dispersed nature of agricultural activities and the need for monitoring, verification, and establishing credible baselines add to the difficulty (Makundi et Sathaye 2009, De Stefano et Jacobson 2017). There is a limited information base and fewer tools available for agroforestry compared to traditional agriculture and forestry, making it harder to build accurate carbon accounting and modelling tools (Schoeneberger 2008, Montagnini & Nair 2004). Uncertainty in global land area estimates under AFS further complicates carbon stock assessments (Nair et al. 2009, Lorenz et al. 2014). Variability in carbon sequestration is high. The extent of carbon sequestered depends on site-specific factors such as biological, climatic, soil, and management conditions, which vary widely (Nair et al 2009, Nath et al. 2020). Different agroforestry practices and land-use changes result in varying levels of SOC stocks, adding to the complexity of measurement (De Stefano et al. 2017, Abbas et al 2017). The profitability of carbon sequestration projects is influenced by the price of carbon in the international market, additional income from agroforestry products, and the costs related to carbon monitoring (Nair et al. 2009, Makundi et al. 2004). However, due to recent innovative monitoring techniques and new tools being developed, the costs should be reduced soon (see the EU HORIZON project **digitaf**[1]). Measuring the carbon mitigation potential of agroforestry is challenging due to methodological difficulties, data limitations, variability in sequestration rates, and economic and policy factors. Addressing these challenges requires improved data collection, standardised methodologies, and greater recognition and support for agroforestry within agricultural and forestry sectors.

**End-users /Stakeholders:** The SOC stock and rate increase of silvoarable agroforestry management compared to conventional agricultural management could offer interesting financial benefits in terms of carbon certification rewards and or other economic incentives. Then, agroforestry could lead to a small, positive impact on income, especially when yields improve or when economic incentives such as biomass production are provided to offset crop yield reductions (Castle et al. 2021, Quinkenstein et al. 2009). However, after initialising a silvoarable system, several years should be taken into account until the SOC sequestration rates are sufficiently high (Quinkenstein et al. 2011). In Mediterranean areas, farmers perceive silvoarable systems as potentially increasing farm profitability due to diversified income sources from both crops and trees (Graves et al. 2009, Palma et al. 2007). Silvoarable systems improve ecosystem services such as soil fertility, carbon sequestration, and erosion control. These systems also enhance biodiversity and nutrient provisioning for the crops (Visscher et al. 2023, Mosquera-Losada et al. 2023, Palma et al. 2007). Also, agroforestry practices can reduce pest and disease incidence by increasing natural enemy abundance and reducing pest populations, particularly in perennial crops (Pumariño et al. 2015, Staton et al. 2019).

[1] https://digitaf.eu/

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

**Policy makers**: Silvoarable agroforestry is a dual-purpose approach which optimises the land use, making it possible to produce more food and biomass per unit area. Given the increasing demand for food and the need for sustainable land use, silvoarable systems offer a viable solution that enhances productivity while maintaining ecological balance. Moreover, silvoarable systems are adaptable to a wide range of agricultural settings, from smallholder farms to large-scale agricultural enterprises. This adaptability makes them a practical and scalable solution for enhancing sustainability in modern agriculture. The carbon mitigation potential of agroforestry is ambivalent. Silvopastoral systems are not offering any advantage compared to traditional livestock management. Interestingly, silvoarable systems are offering a significant carbon mitigation potential in the soil and in the trees. Focusing on the soil carbon mitigation potential, SOC stock can be increased in silvoarable AFS compared to conventional agriculture. Importantly, the SOC sequestration rates are usually increased in silvoarable AFS, regardless the tree and crop species. A majority of studies found rates from 0.5 to 1.5 t C per hectare and year in the topsoil. However, a more precise generic estimate on the SOC rate is highly uncertain, since the set-up of the AFS, such as soil type, climate, tree and crop species, tree density, system age and tillage, is greatly influencing the SOC rate.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# 7. Main conclusions

This deliverable provides an extensive evaluation of the carbon sequestration potential, uncertainties, and co-benefits of CF practices across five key agricultural systems: woody crops, peatlands, arable lands, grasslands, and agroforestry. The findings emphasise both the opportunities and challenges in implementing CF practices effectively.

## 7.1. Key Findings

The report synthesises findings on CF practices across the five systems:

**Woody Crops** (e.g., olive groves, vineyards): Practices such as cover crops, no-tillage, and organic amendments improve soil organic carbon (SOC) and reduce soil erosion. SOC improvements are higher in olive groves and higher SOC levels were observed under no-tillage combined with the application of a mulch of pruning residues and use of cover crops (usually temporary and composed of natural vegetation).

**Peatlands:** Rewetting and conservation practices reduce $CO_2$ emissions and stabilise organic carbon reserves. Rewetting shows substantial potential to mitigate $CO_2$ emissions, with added benefits for water regulation and biodiversity conservation. The need for long-term monitoring to confirm carbon stability was highlighted.

**Arable Lands:** Techniques like no-tillage, improved crop rotations, residue management and addition of organic amendments, and cover crops enhance SOC. Among these, zero tillage demonstrated the highest potential for SOC sequestration. However, this conclusion is primarily based on data derived from topsoil sampling, highlighting the need for further analysis across deeper soil layers.

**Grasslands:** Improved grazing management, reseeding, and legume integration boost carbon sequestration and biodiversity. The conversion of arable lands to grasslands would be the practice with the highest carbon sequestration.

**Agroforestry** (hedgerows, silvopasture): Tree integration into farming landscapes increases long-term carbon storage and ecosystem resilience. Silvoarable systems generally outperform silvopastoral systems in carbon sequestration, with alley cropping showing more consistent outcomes and hedgerows exhibiting greater but more variable potential. Effective management is crucial to maximizing carbon sequestration, especially in silvoarable systems.

## 7.2. Cross-Cutting Challenges

Despite substantial research, CF studies share critical limitations that hinder reliable conclusions:

- Methodological Variability: Differences in sampling depths, bulk density measurements, and definitions of management practices reduce comparability.
- Insufficient Long-Term Data: Few studies track carbon dynamics over multiple years under consistent conditions.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

- Data Gaps: Sparse reporting on key management variables like tree density, plantation age.
- Peatlands Specifics: Challenges in measuring SOC changes in deep peat layers and balancing $CH_4$ trade-offs.

## 7.3. Recommendations

To enhance the reliability and scalability of CF practices:

1. Standardise Methodologies: Develop global frameworks for SOC measurement and reporting, addressing soil depths, bulk density, and coarse material content.

2. Expand Long-Term Studies: Conduct site-specific, multi-year research to capture temporal and spatial variations in carbon dynamics.

3. Promote Comprehensive Monitoring:

- **For peatlands**: Measure GHG fluxes ($CO_2$, $CH_4$, and $N_2O$) rather than relying solely on SOC stocks.

- **For woody crops**: Integrate under-canopy and lane-area sampling.

4. Refine Models: For agroforestry, include impacts of tree species, management practices, and interactions with local conditions.

5. Policy Support: Create incentives for adopting best practices (e.g., rewetting peatlands, agroforestry design, and no-tillage) and support farmer training programs.

# 8. Acknowledgements

This research is funded by the European Union (Grant Agreement: 101112942). The content and viewpoints presented in this document are only those of the MARVIC project author(s). They do not necessarily represent the official positions or opinions of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

# 9. References

## 9.1. Woody crops

Almagro, M., Garcia-Franco, N., & Martínez-Mena, M. (2017). The potential of reducing tillage frequency and incorporating plant residues as a strategy for climate change mitigation in semiarid Mediterranean agroecosystems. Agriculture, Ecosystems and Environment, 246, 210–220. https://doi.org/10.1016/j.agee.2017.05.016

Álvarez, H. A., Jiménez-Muñoz, R., Morente, M., Campos, M., & Ruano, F. (2021). Ground cover presence in organic olive orchards affects the interaction of natural enemies against Prays oleae, promoting an effective egg predation. Agriculture Ecosystems & Environment, 315, 107441. https://doi.org/10.1016/j.agee.2021.107441

Álvarez, S., Soriano, M. A., Landa, B. B., & Gómez, J. A. (2007). Soil properties in organic olive groves compared with that in natural areas in a mountainous landscape in southern Spain. Soil Use And Management, 23(4), 404-416. https://doi.org/10.1111/j.1475-2743.2007.00104.x

Baldi, E., Cavani, L., Margon, A., Quartieri, M., Sorrenti, G., Marzadori, C., & Toselli, M. (2018). Effect of compost application on the dynamics of carbon in a nectarine orchard ecosystem. Science of the Total Environment, 637–638, 918–925. https://doi.org/10.1016/j.scitotenv.2018.05.093

Biddoccu, M., Guzmán, G., Capello, G., Thielke, T., Strauss, P., Winter, S., Zaller, J., Nicolai, A., Cluzeau, D., Popescu, D., Bunea, C., Hoble, A., Cavallo, E., & Gómez, J. (2020). Evaluation of soil erosion risk and identification of soil cover and management factor (C) for RUSLE in European vineyards with different soil management. International Soil And Water Conservation Research, 8(4), 337-353. https://doi.org/10.1016/j.iswcr.2020.07.003

Bombino, G., Denisi, P., Gómez, J. A., & Zema, D. A. (2021). Mulching as best management practice to reduce surface runoff and erosion in steep clayey olive groves. International Soil And Water Conservation Research, 9(1), 26-36. https://doi.org/10.1016/j.iswcr.2020.10.002

Brunori, E., Farina, R., & Biasi, R. (2016). Sustainable viticulture: The carbon-sink function of the vineyard agro-ecosystem. Agriculture, Ecosystems and Environment, 223, 10–21. https://doi.org/10.1016/j.agee.2016.02.012

Callesen, T. O., Gonzalez, C. V., Bastos Campos, F., Zanotelli, D., Tagliavini, M., & Montagnani, L. (2023). Understanding carbon sequestration, allocation, and ecosystem storage in a grassed vineyard. Geoderma Regional, 34. https://doi.org/10.1016/j.geodrs.2023.e00674

Castro-Caro, J. C., Barrio, I. C., Barrio, I. C., & Tortosa, F. S. (2014). Is the effect of farming practices on songbird communities landscape dependent? A case study of olive groves in southern Spain. https://www.semanticscholar.org/paper/Is-the-effect-of-farming-practices-on-songbird-A-of-Castro-Caro-Barrio/0dfe3beb18708f115e7e71766c45e7fe31350a8a

Dao, T. H. (1996). Tillage system and crop residue effects on surface compaction of a Paleustoll. Agronomy Journal, 88(2), 141–148. https://doi.org/10.2134/agronj1996.00021962008800020005x

Eskandari Damaneh, H., Khosravi, H., Habashi, K., Eskandari Damaneh, H., & Tiefenbacher, J. P. (2022). The impact of land use and land cover changes on soil erosion in western Iran. Natural Hazards, 110(3), 2185–2205. https://doi.org/10.1007/s11069-021-05032-w

EUROSTAT, 2024. https://ec.europa.eu/eurostat.

Fernández Hernández, A., Vega Humanes, M., & García-Ortiz Civantos, C. (2015). Compostado y aplicación de alperujo en olivar. Consejería de Agricultura, Pesca y Deporte de Andalucía.

Fernández‐Romero, M. L., Lozano‐García, B., Parras‐Alcántara, L., Collins, C. D., & Clark, J. M. (2014). Effects of Land Management on Different Forms of Soil Carbon in Olive Groves in Mediterranean Areas. Land Degradation And Development, 27(4), 1186-1195. https://doi.org/10.1002/ldr.2327

Gómez, J. A., Álvarez, S., & Soriano, M. (2009). Development of a soil degradation assessment tool for organic olive groves in southern Spain. CATENA, 79(1), 9-17. https://doi.org/10.1016/j.catena.2009.05.002

Gómez, J. A., Campos, M., Guzmán, G., Castillo-Llanque, F., Vanwalleghem, T., Lora, Á., & Giráldez, J. V. (2017). Soil erosion control, plant diversity, and arthropod communities under heterogeneous cover crops in an olive orchard. Environmental Science And Pollution Research, 25(2), 977-989. https://doi.org/10.1007/s11356-016-8339-9

Gómez, J. A., Gómez, J. A., Romero, P., Giráldez, J. V., & Fereres, E. (2005). Experimental assessment of runoff and soil erosion in an olive grove on a Vertic soil in southern Spain as affected by soil management. Soil Use and Management, 20(4), 426–431. https://doi.org/10.1079/sum2004275

Gómez, J. A., Guzmán, G., Vanwalleghem, T., & Vanderlinden, K. (2023). Spatial variability of soil organic carbon stock in an olive orchard at catchment scale in Southern Spain. International Soil And Water Conservation Research, 11(2), 311-326. https://doi.org/10.1016/j.iswcr.2022.12.002

Gómez, J. A., Reyna-Bowen, L., Rebollo, P. F., & Soriano, M. (2022). Comparison of Soil Organic Carbon Stocks Evolution in Two Olive Orchards with Different Planting Systems in Southern Spain. Agriculture, 12(3), 432. https://doi.org/10.3390/agriculture12030432

Gómez, J., Francia, J., Guzmán, G., Vanwalleghem, T., Zuazo, V. D., Castillo, C., Aranda, M., Cárceles, B., Moreno, A., Torrent, J., & Barrón, V. (2017). Lateral Transfer of Organic Carbon and Phosphorus by Water Erosion at Hillslope Scale in Southern Spain Olive Orchards. Vadose Zone Journal, 16(12), 1-15. https://doi.org/10.2136/vzj2017.02.0047

Gómez, J., Infante-Amate, J., De Molina, M., Vanwalleghem, T., Taguas, E., & Lorite, I. (2014). Olive Cultivation, its Impact on Soil Erosion and its Progression into Yield Impacts in Southern Spain in the Past as a Key to a Future of Increasing Climate Uncertainty. Agriculture, 4(2), 170-198. https://doi.org/10.3390/agriculture4020170

Gómez, J., Rodríguez-Carretero, M., Lorite, I., & Fereres, E. (2015). Modeling to Evaluate and Manage Climate Change Effects on Water Use in Mediterranean Olive Orchards with Respect to Cover Crops and Tillage Management. En Advances in agricultural systems modeling (pp. 237-265). https://doi.org/10.2134/advagricsystmodel5.c10

Gómez, J.A. 2017. Sustainability using cover crops in mediterranean tree crops, olives and vines – challenges and current knowledge. Hungarian Geographical Bulletin 66:13-28

Gómez, J.A., Giráldez, J.V., Pastor, M., Fereres, E. (1999). Effects of tillage method on soil physical properties, infiltration and yield in an olive orchard. Soil And Tillage Research, 52(3-4), 167-175. https://doi.org/10.1016/s0167-1987(99)00078-1

Gómez, J.A., Guzmán, G., Lorite, I., Soriano, M.A., Cubiertas vegetales, balance de agua y efecto en cosecha con respecto a laboreo: Una mirada a información generada durante décadas. Proceedings of Expoliva 2023. https://www.expoliva.com/baseconocimiento/comunicaciones-foro-olivar-expoliva-2023/#OLI-28

Gómez-Muñoz, B., Valero-Valenzuela, J. D., Hinojosa, M. B., & García-Ruiz, R. (2016). Management of tree pruning residues to improve soil organic carbon in olive groves. European Journal of Soil Biology, 74, 104–113. https://doi.org/10.1016/j.ejsobi.2016.03.010

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., … Fargione, J. (2017). Natural climate solutions. Proceedings of the National Academy of Sciences of the United States of America, 114(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

Guzmán, G., Cabezas, J., Sánchez-Cuesta, R., Lora, Á., Bauer, T., Strauss, P., Winter, S., Zaller, J., & Gómez, J. (2019). A field evaluation of the impact of temporary cover crops on soil properties and vegetation communities in southern Spain vineyards. Agriculture Ecosystems & Environment, 272, 135-145. https://doi.org/10.1016/j.agee.2018.11.010

Kay, S., Rega, C., Moreno, G., den Herder, M., Palma, J. H. N., Borek, R., Crous-Duran, J., Freese, D., Giannitsopoulos, M., Graves, A., Jäger, M., Lamersdorf, N., Memedemin, D., Mosquera-Losada, R., Pantera, A., Paracchini, M. L., Paris, P., Roces-Díaz, J. V., Rolo, V., … Herzog, F. (2019). Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Policy, 83, 581–593. https://doi.org/10.1016/j.landusepol.2019.02.025

Keightley, K. E. (2011). Applying new methods for estimating in vivo vineyard carbon storage. American Journal of Enology and Viticulture, 62(2), 214–218. https://doi.org/10.5344/ajev.2010.10081

Kim, N., Zabaloy, M. C., Guan, K., & Villamil, M. B. (2020). Do cover crops benefit soil microbiome? A meta-analysis of current research. Soil Biology And Biochemistry, 142, 107701. https://doi.org/10.1016/j.soilbio.2019.107701

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Kratschmer, S., Pachinger, B., Schwantzer, M., Paredes, D., Guzman, G., Gomez, J. A., Entrenas, J. A., Guernion, M., Burel, F., Nicolai, A., Fertil, A., Popescu, D., Macavei, L., Hoble, A., Bunea, C., Kriechbaum, M., Zaller, J. G., & Winter, S. (2019). Response of wild bee diversity, abundance, and functional traits to vineyard inter‐row management intensity and landscape diversity across Europe. Ecology And Evolution, 9(7), 4103-4115. https://doi.org/10.1002/ece3.5039

Landa, B. B., Montes‐Borrego, M., Aranda, S., Soriano, M. A., Gómez, J. A., & Navas‐Cortés, J. A. (2014). Soil factors involved in the diversity and structure of soil bacterial communities in commercial organic olive orchards in Southern Spain. Environmental Microbiology Reports, 6(2), 196-207. https://doi.org/10.1111/1758-2229.12148

Lazcano, C., Gonzalez-Maldonado, N., Yao, E. H., Wong, C. T. F., Falcone, M., Dodson Peterson, J., Casassa, L. F., Malama, B., & Decock, C. (2022). Assessing the Short-Term Effects of No-Till on Crop Yield, Greenhouse Gas Emissions, and Soil C and N Pools in a Cover-Cropped, Biodynamic Mediterranean Vineyard. Australian Journal of Grape and Wine Research, 2022. https://doi.org/10.1155/2022/8100818

Liebhard, G., Guzmán, G., Gómez, J. A., Winter, S., Zaller, J. G., Bauer, T., Nicolai, A., Cluzeau, D., Popescu, D., Bunea, C., & Strauss, P. (2024). Vineyard cover crop management strategies and their effect on soil properties across Europe. European Journal Of Soil Science, 75(5). https://doi.org/10.1111/ejss.13573

Liguori, G., Gugliuzza, G., & Inglese, P. (2009). Evaluating carbon fluxes in orange orchards in relation to planting density. Journal of Agricultural Science, 147(6), 637–645. https://doi.org/10.1017/S002185960900882X

Litskas, V., Ledo, A., Lawrence, P., Chrysargyris, A., Giannopoulos, G., Heathcote, R., Hastings, A., Tzortzakis, N., & Stavrinides, M. (2022). Use of Winery and Animal Waste as Fertilizers to Achieve Climate Neutrality in Non-Irrigated Viticulture. Agronomy, 12(10). https://doi.org/10.3390/agronomy12102375

Llorca, R., Lidón, A., Ortí, JM., Bautista, I. (2004). Influencia de una cubierta de residuos de poda sobre un suelo cultivado de cítricos. Actas del XXII Congreso Nacional de Riegos. Consejería de Agricultura y Desarrollo Económico, Gobierno de la Rioja. ISBN: 84-8125231- X.

López-Bellido Garrido, P. J. (2017). Balance y huella de carbono en plantaciones de olivar en el sur de España. Córdoba, España: Universidad de Córdoba. [Tesis Doctoral].

Martínez-Núñez, C., Rey, P. J., Salido, T., Manzaneda, A. J., Camacho, F. M., & Isla, J. (2021). Ant community potential for pest control in olive groves: Management and landscape effects. Agriculture, Ecosystems and Environment, 305. https://doi.org/10.1016/j.agee.2020.107185

Montanaro, G., Celano, G., Dichio, B., & Xiloyannis, C. (2010). Effects of soil-protecting agricultural practices on soil organic carbon and productivity in fruit tree orchards. Land Degradation and Development, 21(2), 132–138. https://doi.org/10.1002/ldr.917

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Morandé, J. A., Stockert, C. M., Liles, G. C., Williams, J. N., Smart, D. R., & Viers, J. H. (2017). From berries to blocks: Carbon stock quantification of a California vineyard. Carbon Balance and Management, 12(1). https://doi.org/10.1186/s13021-017-0071-3

Muhammad, I., Wang, J., Sainju, U. M., Zhang, S., Zhao, F., & Khan, A. (2021). Cover cropping enhances soil microbial biomass and affects microbial community structure: A meta-analysis. Geoderma, 381, 114696. https://doi.org/10.1016/j.geoderma.2020.114696

Nordrhein-Westfalen, M. F. I. W. U. F. D. L., Innovation, E. U. F. F. H. E. R. D. A., De Economía y Competitividad, M., & De Educación y Cultura, M. (2019, 25 octubre). Diverging effects of landscape factors and inter-row management on the abundance of beneficial and herbivorous arthropods in andalusian vineyards (Spain). DIGITAL.CSIC. https://digital.csic.es/handle/10261/193494

Pitacco, A., & Meggio, F. (2015). Carbon budget of the vineyard – A new feature of sustainability. BIO Web of Conferences, 5, 01024. https://doi.org/10.1051/bioconf/20150501024

Proietti, P., Sdringola, P., Brunori, A., Ilarioni, L., Nasini, L., Regni, L., Pelleri, F., Desideri, U., & Proietti, S. (2016). Assessment of carbon balance in intensive and extensive tree cultivation systems for oak, olive, poplar and walnut plantation. Journal of Cleaner Production, 112, 2613–2624. https://doi.org/10.1016/j.jclepro.2015.10.009

Proietti, S., Sdringola, P., Desideri, U., Zepparelli, F., Brunori, A., Ilarioni, L., Nasini, L., Regni, L., & Proietti, P. (2014). Carbon footprint of an olive tree grove. Applied Energy, 127, 115–124. https://doi.org/10.1016/j.apenergy.2014.04.019

Prosdocimi, M., Tarolli, P., & Cerdà, A. (2016). Mulching practices for reducing soil water erosion: A review. In Earth-Science Reviews (Vol. 161, pp. 191–203). Elsevier B.V. https://doi.org/10.1016/j.earscirev.2016.08.006

Repullo, M. A., Carbonell, R., Hidalgo, J., Rodríguez-Lizana, A., & Ordóñez, R. (2012). Using olive pruning residues to cover soil and improve fertility. Soil and Tillage Research, 124, 36–46. https://doi.org/10.1016/j.still.2012.04.003

Rubio-Asensio, J. S., Abbatantuono, F., Ramírez-Cuesta, J. M., Hortelano, D., Ruíz, J. L., Parra, M., Martínez-Meroño, R. M., Intrigliolo, D. S., & Buesa, I. (2022). Effects of Cover Crops and Drip Fertigation Regime in a Young Almond Agroecosystem. Agronomy, 12(11). https://doi.org/10.3390/agronomy12112606

Sastre, B., Bienes, R., & Cuevas, A. (2016). Incidencia de las cubiertas vegetales sobre la infiltración del agua de lluvia. https://www.researchgate.net/publication/301351776

Scandellari, F., Caruso, G., Liguori, G., Meggio, F., Palese Assunta, M., Zanotelli, D., Celano, G., Gucci, R., Inglese, P., Pitacco, A., & Tagliavini, M. (2016). A survey of carbon sequestration potential of orchards and vineyards in Italy. European Journal of Horticultural Science, 81(2), 106–114. https://doi.org/10.17660/eJHS.2016/81.2.4

Sharifi, M., & Hajiaghaei-Kamrani, M. (2023). Biochar–compost mixture and cover crop effects on soil carbon and nitrogen dynamics, yield, and fruit quality in an irrigated vineyard. Canadian Journal of Soil Science, 103(1), 200–212. https://doi.org/10.1139/cjss-2021-0147

Song, R., Zhu, Z., Zhang, L., Li, H., & Wang, H. (2023). A Simple Method Using an Allometric Model to Quantify the Carbon Sequestration Capacity in Vineyards. Plants, 12(5). https://doi.org/10.3390/plants12050997

Soriano, M.A., Cabezas, J.M., Gómez, J.A. 2018. Soil water content and yield a vertisol in a rain-fed olive grove under four different soil management practices in a four year experiment. Geophysical Research Abstracts Vol. 20, EGU2018-5390. https://meetingorganizer.copernicus.org/EGU2018/EGU2018-5390.pdf

Steenwerth, K., & Belina, K. M. (2008). Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem. Applied Soil Ecology, 40(2), 359–369. https://doi.org/10.1016/j.apsoil.2008.06.006

Torres, J. A., García-fuentes, A., Ruiz, L., Siles, G., Valle Tendero, F., & Fernández Ondoño, E. (2016). Ganado ovino como herramienta para el control de la cubierta vegetal en el olivar ecológico: diversificación de la riqueza. Agroinforme, 60-63.

Torrús-Castillo, M., Calero, J., & García-Ruiz, R. (2023). Does olive cultivation sequester carbon?: Carbon balance along a C input gradient. Agriculture, Ecosystems and Environment, 358. https://doi.org/10.1016/j.agee.2023.108707

Torrús-Castillo, M., Domouso, P., Herrera-Rodríguez, J. M., Calero, J., & García-Ruiz, R. (2022). Aboveground Carbon Fixation and Nutrient Retention in Temporary Spontaneous Cover Crops in Olive Groves of Andalusia. Frontiers in Environmental Science, 10. https://doi.org/10.3389/fenvs.2022.868410

Vendrame, N., Tezza, L., & Pitacco, A. (2019). Study of the carbon budget of a temperate-climate vineyard: Inter-annual variability of CO 2 flux. American Journal of Enology and Viticulture, 70(1), 34–41. https://doi.org/10.5344/ajev.2018.18006

Vicente-Vicente, J. L., García-Ruiz, R., Francaviglia, R., Aguilera, E., & Smith, P. (2016). Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis. Agriculture, Ecosystems & Environment, 235, 204–214. https://doi.org/10.1016/j.agee.2016.10.024

Winter, S., Bauer, T., Strauss, P., Kratschmer, S., Paredes, D., Popescu, D., Landa, B., Guzmán, G., Gómez, J. A., Guernion, M., Zaller, J. G., & Batáry, P. (2018). Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: A meta-analysis. Journal Of Applied Ecology, 55(5), 2484-2495. https://doi.org/10.1111/1365-2664.13124

Wolff, M. W., Alsina, M. M., Stockert, C. M., Khalsa, S. D. S., & Smart, D. R. (2018). Minimum tillage of a cover crop lowers net GWP and sequesters soil carbon in a California vineyard. Soil and Tillage Research, 175, 244–254. https://doi.org/10.1016/j.still.2017.06.003

Wong, C. T. F., Falcone, M., Rich, G., Stubler, C., Malama, B., Lazcano, C., & Decock, C. (2023). Short-term effects of increasing compost application rates on soil C and greenhouse gas (N2O and CO2) emissions in a California central coast vineyard. Frontiers in Environmental Science, 11. https://doi.org/10.3389/fenvs.2023.1123510

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Zhao, M., Li, M., & Shi, Y. (2015). Effect of plantation ages, densities and management strategies on carbon sequestration in tropical mango and wax apple orchard ecosystems.

Zumkeller, M., Yu, R., Torres, N., Marigliano, L. E., Zaccaria, D., & Kurtural, S. K. (2022). Site characteristics determine the effectiveness of tillage and cover crops on the net ecosystem carbon balance in California vineyard agroecosystems. Frontiers in Plant Science, 13. https://doi.org/10.3389/fpls.2022.1024606

## 9.2. Peatlands

Aben, R.C.H., van de Craats, D., Boonman, J., Peeters, S.H., Vriend, B., Boonman, C.C.F., van der Velde, Y., Erkens, G., van den Berg, M. (2024). Using automated transparent chambers to quantify CO2 emissions and potential emission reduction by water infiltration systems in drained coastal peatlands in the Netherlands. EGUsphere 2024, 1-31.

Bianchi, A., Larmola, T., Kekkonen, H., Saarnio, S., Lång, K. (2021). Review of Greenhouse Gas Emissions from Rewetted Agricultural Soils. Wetlands 41(8), 108.

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Baerisch, S., Dubovik, D., Liashchynskaya, N., Michaelis, D., Minke, M., Skuratovich, A., Joosten, H. (2011). Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. Hydrobiologia 674(1), 67-89.

Deng, J., Li, C., Frolking, S. (2015). Modeling impacts of changes in temperature and water table on C gas fluxes in an Alaskan peatland. Journal of Geophysical Research: Biogeosciences 120(7), 1279-1295.

Evans, C.D., Peacock, M., Baird, A.J., Artz, R.R.E., Burden, A., Callaghan, N., Chapman, P.J., Cooper, H.M., Coyle, M., Craig, E., Cumming, A., Dixon, S., Gauci, V., Grayson, R.P., Helfter, C., Heppell, C.M., Holden, J., Jones, D.L., Kaduk, J., Levy, P., Matthews, R., McNamara, N.P., Misselbrook, T., Oakley, S., Page, S.E., Rayment, M., Ridley, L.M., Stanley, K.M., Williamson, J.L., Worrall, F., Morrison, R. (2021). Overriding water table control on managed peatland greenhouse gas emissions. Nature 593(7860), 548-552.

IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Switzerland.

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Koch, J., Elsgaard, L., Greve, M.H., Gyldenkærne, S., Hermansen, C., Levin, G., Wu, S., Stisen, S. (2023). Water-table-driven greenhouse gas emission estimates guide peatland restoration at national scale. Biogeosciences 20(12), 2387-2403.

Lin, F., Zuo, H., Ma, X., Ma, L. (2022). Comprehensive assessment of nitrous oxide emissions and mitigation potentials across European peatlands. Environmental Pollution 301, 119041.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Paul, S., Ammann, C., Alewell, C., Leifeld, J. (2021). Carbon budget response of an agriculturally used fen to different soil moisture conditions. Agricultural and Forest Meteorology 300, 108319.

Paul, S., Ammann, C., Wang, Y., Alewell, C., Leifeld, J. (2024). Can mineral soil coverage be a suitable option to mitigate greenhouse gas emissions from agriculturally managed peatlands? Agriculture, Ecosystems & Environment 375, 109197.

Silva, M.P., Healy, M.G., Gill, L. (2024). Reviews and syntheses: A scoping review evaluating the potential application of ecohydrological models for northern peatland restoration. Biogeosciences 21(13), 3143-3163.

Swails, E., Hergoualc'h, K., Deng, J., Frolking, S., Novita, N. (2022). How can process-based modeling improve peat $CO_2$ and $N_2O$ emission factors for oil palm plantations? Science of The Total Environment 839, 156153.

Tanneberger, F., Berghöfer, A., Brust, K., Hammerich, J., Holsten, B., Joosten, H., Michaelis, D., Moritz, F., Reichelt, F., Schäfer, A., Scheid, A., Trepel, M., Wahren, A., Couwenberg, J. (2024). Quantifying ecosystem services of rewetted peatlands − the MoorFutures methodologies. Ecological Indicators 163, 112048.

Tiemeyer, B., Freibauer, A., Borraz, E.A., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Ebli, M., Eickenscheidt, T., Fiedler, S., Förster, C., Gensior, A., Giebels, M., Glatzel, S., Heinichen, J., Hoffmann, M., Höper, H., Jurasinski, G., Laggner, A., Leiber-Sauheitl, K., Peichl-Brak, M., Drösler, M. (2020). A new methodology for organic soils in national greenhouse gas inventories: Data synthesis, derivation and application. Ecological Indicators 109, 105838.

UNEP. (2022). Global Peatlands Assessment – The State of the World's Peatlands: Evidence for action toward the conservation, restoration, and sustainable management of peatlands., Global Peatland Initiative. United Nations Environment Programme, Nairobi.

Wang, Y., Calanca, P., Leifeld, J. (2024). Sources of nitrous oxide emissions from agriculturally managed peatlands. Global Change Biology 30(1), e17144.

Willenbockel, D. (2024). Peatland restoration in Germany: A dynamic general equilibrium analysis. Ecological Economics 220, 108187.

## 9.3. Arable lands

Abdalla, K., Chivenge, P., Ciais, P., Chaplot, V. (2016). No-tillage lessens soil CO2 emissions the most under arid and sandy soil conditions: results from a meta-analysis. Biogeosciences, 13:3619–3633. https://doi.org/10.5194/bg-13-3619-2016.

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

Aytenew, M., Wolancho, G.B. (2020). Effects of Organic Amendments on Soil Fertility and Environmental Quality: A Review. Journal of Plant Sciences, 8:112-119. https://doi.org/10.11648/j.jps.20200805.12

Bai, Z., Caspari , T., Ruiperez Gonzalez, M., Batjes, N.H., Mäder, P., Bünemann, E.K., de Goede, R., Braussaard, L., Xu, M., Santos Ferreira, C.S., Reintam, E., Fan, H., Mihelič, R., Glavan, M., Tóth, Z. (2018). Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. Agriculture, Ecosystems & Environment, 265:1-7. https://doi.org/10.1016/j.agee.2018.05.028.

Beillouin, D., Corbeels, M., Demenois, J., Berre, D., Boyer, A., Fallot, A., Feder, F., Cardinael, R. (2023). A global meta-analysis of soil organic carbon in the Anthropocene. Nature Communications, 14:1-10. https://doi.org/10.1038/s41467-023-39338-z.

Brombin, V., Mistri, E., De Feudis, M., Forti, C., Salani, G.M., Natali, C., Falsone, G., Antisari, L.V., Bianchini, G. (2020). Soil Carbon Investigation in Three Pedoclimatic and Agronomic Settings of Northern Italy. Sustainability, 12:1-19. https://doi.org/10.3390/su122410539..

Brevik, E., Fenton, T., Moran, L. (2002). Effects of soil compaction on organic carbon amounts and distribution, South-Central Iowa. Environmental Pollution, 116:137-141. https://doi.org/10.1016/S0269-7491(01)00266-4.

Buckwell, A., Nadeu, E., Williams, A. (2022). Sustainable Agricultural Soil Management: What´s stopping it? How can it be enabled? RISE Foundation, Brussels.

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

Frelih-Larsen, A., Leipprand, A., Naumann, S., Beucher, O. (2008). Climate change mitigation through agricultural techniques: Policy recommendations. PICCMAT - Policy Incentives for Climate Change Mitigation Agricultural Techniques.

González-Sánchez, E.J., Ordóñez-Fernández, R., Carbonell-Bojollo, R., Veroz-González, O., Gil-Ribes, G.A. 2012. Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture. Soil & Tillage Research, 122:52-60. https://doi.org/10.1016/j.still.2012.03.001.

Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B., Isberg, P.E. (2017). How does tillage intensity affect soil organic carbon? A systematic review. Environmental Evidence, 6:1-48. https://doi.org/10.1186/s13750-017-0108-9.

Heikkinen, J., Kurganova, I., de Gerenyu, V.L., Palosuo, T., Regina, K. (2014). Changes in soil carbon stock after cropland coversion to grassland in Russian temperate zone: measurements versus model simulation. Nutrient Cycling in Agroecosystems, 98:97-106. https://doi.org/10.1007/s10705-014-9599-8.

Hepburn, C, Adlen, E., Beddington, J., Carter, E., Fuss, S., Mac Dowell, N., Minx, J., Smith, P., Williams, C. (2019). The technological and economic prospects for CO2 utilization and removal. Nature 575(7781): 87-97. https://doi.org/10.1038/s41586-019-1681-6.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Holland, J.M. (2004). The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agriculture, Ecosystems & Environment, 103:1-25. https://doi.org/10.1016/j.agee.2003.12.018.

Huang, F., Ding, X., Li, W., Jia, H., Wei, X., Zhao, X. (2021). The effect of temperature on the decomposition of diferent parts of maize residues in a solonchak. Catena, 201:1-11. https://doi.org/10.1016/j.catena.2021.105207.

Jarecki, M.K., Lal, R. (2003). Crop Management for Soil Carbon Sequestration. Critical Reviews in Plant Sciences, 22:471-502. https://doi.org/10.1080/713608318.

Jian, J., Du, X., Reiter, M.S., Stewart, R.D. (2020). A meta-analysis of global cropland carbon changes due to cover cropping. Soil Biology and Biochemistry, 143:1-11. https://doi.org/10.1016/j.soilbio.2020.107735

Joshi, D.R., Sieverding, H.L., Xu, H., Kwon, H., Wang, M., Clay, S.A., Johnson, J.M., Tapa, R., Westhoff, S., Clay, D.E. (2023). A global meta-analysis of cover crop response on soil carbon storage within a corn production system. Agronomy Journal, 115:1543-1556. https://doi.org/10.1002/agj2.21340.

Kragt, M.E., Robertson, M.J. (2014). Quantifying ecosystem services trade-offs from agricultural practices. Ecological Economics, 102:147–157. https://doi.org/10.1016/j.ecolecon.2014.04.001.

Krauss, M., Wiesmeier, M., Don, A., Cuperus, F., Gattinger, A., Gruber, S., Haagsma, W.K., Peigné, J., Chiodelli Palazzoli, M., Schulz, F., van der Heijden, M.G.A., Vincent-Caboud, L., Wittwer, R.A., Zikeli, S., Steffens, M. (2022). Reduced tillage in organic farming affects soil organic carbon stocks in temperate Europe. Soil and Tillage Research, 216:1-11. https://doi.org/10.1016/j.still.2021.105262.

Kumari, A., P, A., Tiwari, P., Sachan, P., Malla, A.K., Tripathy, A., Chowdhury, M. (2023). Zero Tillage Lead to Enhanced Productivity and Soil Health. International Journal of Environment and Climate Change. https://doi.org/10.9734/IJECC/2023/v13i103042.

Lugato, E., Bampa, F., Panagos, P., Montanarella, L., Jones, A. (2015). Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. Global Change Biology, 20:3557-3567. https://doi.org/10.1111/gcb.12551.

Martineau, H., Wiltshire, J., Webb, J., Hart, K., Keenleyside, C., Baldock, D., Bell, H., Watterson, J. (2016). Effective performance of tools for climate action policy - meta-review of Common Agricultural Policy (CAP) mainstreaming. Report for European Commission - DG Climate Action.

McDonald, H. et al. (2021a). Certification of Carbon Removals. Part 2: A review of carbon removal certification supports and methodologies. Environment Agency Austria, Vienna.

McDonald, H., Frelih-Larsen, A., Lóránt, A., Duin, L., Bradley, H. (2021b). Carbon farming. Making agriculture fit for 2030. Report to the European Parliament, Brussels.

Minasny, B., Malone, P.B., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y.,



Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, Ch-Ch., Vågen, T-G., van Wesemael, B., Winowiecki, L. (2017). Soil carbon 4 per mille. Geoderma, 292:59-86. http://dx.doi.org/10.1016/j.geoderma.2017.01.002.

Moukanni, N., Brewer, K.M., Gaudin, A.C.M., O´Geen, A.T. (2022). Optimizing Carbon Sequestration Through Cover Cropping in Mediterranean Agroecosystems: Synthesis of Mechanisms and Implications for Management. Frontiers in Agronomy, 4:1-19. https://doi.org/10.3389/fagro.2022.844166.

Olson, K.R., Al-Kaisi, M.M. (2015). The importance of soil sampling depth for accurate amount of soil organic carbon sequestration, storage, retention and loss. Catena, 125:33-37. https://doi.org/10.1016/j.catena.2014.10.004.

Powlson, D. S., Bhogal, A., Chambers, B. J., Coleman K., Macdonald, A.J., Goulding, K.W.T., Whitmore, A.P. (2012). The potential to increase soil carbon stocks through reduced tillage or organic material conditions in England and Wales: A case study. Agriculture, Ecosystems and Environment, 146:23-33. https://doi.org/10.1016/j.agee.2011.10.004.

Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M. et al. (2021). Land-based measures to mitigate climate change: Potential and feasibility. Global Change Biology, 27:6025–6058. https://doi.org/10.1111/gcb.15873.

Rosa-Schleich, J., Loos, J., Mußhoff, O., Tscharntke., T. (2019). Ecological-economic trade-offs of Diversified Farming Systems – A review. Ecological Econmics, 160:251–263. https://doi.org/10.1016/j.ecolecon.2019.03.002.

Sarauskis, E., Buragiene, S., Romaneckas, K., Masilionyte, L., Kriauciuniene, Z., Sakalauskas, A., Jasinskas, A., Karayel, D. (2014). Deep, shallow and no-tillage effects on soil compaction parameters. Engineering for rural development, Jelgava.

Schils, R., Kuikman, P., Liski, J., van Oijen, M., Smith, P., Webb, J., Alm, J., Somogyi, Z., van den Akker, J., Billett, M., Emmett, B., Evans, Ch., Lindner, M., Palosuo, T., Bellamy, P., Alm, J., Jandl, R., Hiederer, R. (2008). Review of existing information on the interrelations between soil and climate change. Final report. CLIMSOIL.

Sharma, P., Singh, A., Kahlon, C.S., Brar, A.S., Grover, K.K., Dia, M., Steiner, R.L. (2018). The Role of Cover Crops towards Sustainable Soil Health and Agriculture – A Review Paper. American Journal of Plant Sciences, 9:1935-1951. https://doi.org/10.4236/ajps.2018.99140.

Smith, P., Andrén, O., Karlsson, T., Perälä, P., Regina, K., Rounsevell, M., Van Wesemael, B. (2005). Carbon sequestration potential in European croplands has been overestimated. Global Change Biology, 11:2153-2163. https://doi.org/10.1111/j.1365-2486.2005.01052.x.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O´Mara, F., Rice, Ch., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J. (2008). Greenhouse gas mitigation in agriculture. Philos Trans R Soc Lond B Biol Sci, 363:789-813. https://doi.org/10.1098/rstb.2007.2184.

Smith, P., Olesen, J.E. (2010). Synergies between the mitigation of, and adaptation to, climate change in agriculture. Journal of Agricultural Science, 148:543–552. https://doi.org/10.1017/S0021859610000341.

Tiefenbacher, A., Sandén, T., Haslmayr, H-P., Miloczki, J., Wenzel, W., Spiegel, H. (2021). Optimizing Carbon Sequestration in Croplands: A Synthesis. Agronomy, 11:1-28. https://doi.org/10.3390/agronomy11050882.

Tobiašová, E., Lemanowicz, J., Dębska, B., Kunkelová, M., Sakáč, J. (2023). The Effect of Reduced and Conventional Tillage Systems on Soil Aggregates and Organic Carbon Parameters of Different Soil Types. Agriculture, 13:1-12. https://doi.org/10.3390/agriculture13040818.

Turmel, M-S., Speratti, A., Baudron, F., Verhulst, N., Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. Agricultural Systems, 134:6-16. https://doi.org/10.1016/j.agsy.2014.05.009.

Vicente-Vicente, J.L., García-Ruiz, R., Francaviglia, R., Aguilera, E., Smith, P. (2016). Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis. Agriculture, Ecosystems and Environment, 235:204-214. https://doi.org/10.1016/j.agee.2016.10.024.

Vleeshouwers, L.M., Verhagen, A. (2002). Carbon emission and sequestration by agricultural land use: a model study for Europe. Global Change Biology, 8:519-530. https://doi.org/10.1046/j.1365-2486.2002.00485.x.

West, T.O., Six, J. (2007). Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. Climatic Change, 80:25-41. https://doi.org/10.1007/s10584-006-9173-8.

Wu, B., Zhang, M., Zhai, Z., Dai, H., Yang, M., Zhang, Y., Liang, T. (2024). Soil organic carbon, carbon fractions, and microbial community under various organic amendments. Scientific Reports, 14:1-11. https://doi.org/10.1038/s41598-024-75771-w.

Yu, T., Mahe, L., Li, Y., Wei, X., Deng, X., Zhang, D. (2022). Benefits of Crop Rotation on Climate Resilience and Its Prospects in China. Agronomy, 12:1-18. https://doi.org/10.3390/agronomy12020436

## 9.4. Grasslands

Bai, Y., Cotrufo, M.F. (2022). Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science, 377:603-608. https://doi.org/10.1126/science.abo2380.

Balasubramanian, D., Zhou, W-J., Ji, H-L., Grace, J., Bai, X-L., Song, Q-H., Liu, Y-T., Sha, L-Q., Fei, X-H., Zhang, X., Zhao, J-B., Zhao, J-F., Tan, Z-H., Zhang, Y-P. (2020). Environmental and management controls of soil carbon storage in grasslands of southwestern China.

Journal of Environmental Management, 254:1-10. https://doi.org/10.1016/j.jenvman.2019.109810.

Brombin, V., Mistri, E., De Feudis, M., Forti, C., Salani, G.M., Natali, C., Falsone, G., Antisari, L.V., Bianchini, G. (2020). Soil Carbon Investigation in Three Pedoclimatic and Agronomic Settings of Northern Italy. Sustainability, 12:1-19. https://doi.org/10.3390/su122410539.

Buckwell, A., Nadeu, E., Williams, A. (2022). Sustainable Agricultural Soil Management: What´s stopping it? How can it be enabled? RISE Foundation, Brussels.

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

Conant, R.T., Cerri, C.E.P., Osborne, B.B., Paustian, K. (2017). Grassland management impacts on soil carbon stocks: a new synthesis. Ecological Applications, 27:662-668. https://doi.org/10.1002/eap.1473.

Cowie, A. L., Lonergan, V. E., Rabbi, S. M. F., Fornasier, F., Macdonald, C., Harden, S., Kawasaki, A., Singh, B. K. (2013). Impact of carbon farming practices on soil carbon in Northern South Wales. Soil Research, 51:707-718. https://doi.org/10.1071/SR13043.

Ding, S., van der Plas, F., Li, J., Liu, B., Xu, M., Xu, T., Pan, X., Chang, Q., Chen, Y., Li, Y. (2024). Grazing effects on the relationship between plant functional diversity and soil carbon sequestration regulated by livestock species. Journal of Plant Ecology, 17:1-12. https://doi.org/10.1093/jpe/rtae016.

Follett, R. F., Kimble, J. M., Lal, R. (2001). The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. CRC Press LLC, Boca Raton.

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

Frelih-Larsen, A., Leipprand, A., Naumann, S., Beucher, O. (2008). Climate change mitigation through agricultural techniques: Policy recommendations. PICCMAT - Policy Incentives for Climate Change Mitigation Agricultural Techniques.

Ghosh, P.K., Mahanta, S.K. (2014). Carbon sequestration in grassland systems. Range Management and Agrogorestry,, 35:173-181.

Heikkinen, J., Kurganova, I., de Gerenyu, V.L., Palosuo, T., Regina, K. (2014). Changes in soil carbon stock after cropland coversion to grassland in Russian temperate zone: measurements versus model simulation. Nutrient Cycling in Agroecosystems, 98:97-106. https://doi.org/10.1007/s10705-014-9599-8.

Hepburn, C, Adlen, E., Beddington, J., Carter, E., Fuss, S., Mac Dowell, N., Minx, J., Smith, P., Williams, C. (2019). The technological and economic prospects for $CO_2$ utilization and removal. Nature 575(7781): 87-97. https://doi.org/10.1038/s41586-019-1681-6.

Hutchinson, J.J., Campbell, C.A., Desjardins, R.L. 2007. Some perspectives on carbon sequestration in agriculture. Agricultural and Forest Meteorology, 142:288-302. https://doi.org/:10.1016/j.agrformet.2006.03.030.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Lugato, E., Bampa, F., Panagos, P., Montanarella, L., Jones, A. (2015). Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. Global Change Biology, 20:3557-3567. https://doi.org/10.1111/gcb.12551.

McDonald, H. et al. (2021a). Certification of Carbon Removals. Part 2: A review of carbon removal certification supports and methodologies. Environment Agency Austria, Vienna.

McDonald, H., Frelih-Larsen, A., Lóránt, A., Duin, L., Bradley, H. (2021b). Carbon farming. Making agriculture fit for 2030. Report to the European Parliament, Brussels.

Minasny, B., Malone, P.B., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, Ch-Ch., Vågen, T-G., van Wesemael, B., Winowiecki, L. (2017). Soil carbon 4 per mille. Geoderma, 292:59-86. http://dx.doi.org/10.1016/j.geoderma.2017.01.002.

Olson, K.R., Al-Kaisi, M.M. (2015). The importance of soil sampling depth for accurate amount of soil organic carbon sequestration, storage, retention and loss. Catena, 125:33-37. https://doi.org/10.1016/j.catena.2014.10.004.

Petersen, S.O. (2018). Greenhouse gas emissions from liquid dairy manure: Prediction and mitigation. Journal of Dairy Science, 101:6642-6654. https://doi.org/10.3168/jds.2017-13301.

Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M. et al. (2021). Land-based measures to mitigate climate change: Potential and feasibility. Global Change Biology, 27:6025–6058. https://doi.org/10.1111/gcb.15873.

Senapati, N., Chabbi, A., Gastal, F., Smith, P., Mascher, N., Loubet, B., Cellier, P., Naisse, Ch. (2014). Net carbon storage measured in a mowed and grazed temperate sown grassland shows potential for carbon sequestration under grazed system. Carbon Management, 5:131-144. https://doi.org/10.1080/17583004.2014.912863.

Sharma, R., Kandel, S., Khadka, S., Chaudhary, S. (2022). Nutrient contents in different sources of organic manures used in different farms of Bhaktapur district, Nepal. Journal of Agriculture and Natural Resources, 5:150-156. https://doi.org/10.3126/janr.v5i1.50705.

Skinner, H., Dell, C.J., Yield and Soil Carbon Sequestration in Grezed Pastures Sown with Two or Five Forage Species. Crop Science, 56:2035-2044. https://doi.org/10.2135/cropsci2015.11.0711.

Smith, P., Andrén, O., Karlsson, T., Perälä, P., Regina, K., Rounsevell, M., Van Wesemael, B. (2005). Carbon sequestration potential in European croplands has been overestimated. Global Change Biology, 11:2153-2163. https://doi.org/10.1111/j.1365-2486.2005.01052.x.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O´Mara, F., Rice, Ch., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J. (2008). Greenhouse gas mitigation in agriculture. Philos Trans R Soc Lond B Biol Sci, 363:789-813. https://doi.org/10.1098/rstb.2007.2184.

Vleeshouwers, L.M., Verhagen, A. (2002). Carbon emission and sequestration by agricultural land use: a model study for Europe. Global Change Biology, 8:519-530. https://doi.org/10.1046/j.1365-2486.2002.00485.x.

West, T.O., Six, J. (2007). Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. Climatic Change, 80:25-41. https://doi.org/10.1007/s10584-006-9173-8..

Whitehead, D., Schipper, L. A., Pronger, J., Moinet, G. Y. K., Mudge, P. L., Pereira, R. C., Kirschbaum, M. U. F., McNally, S. R., Beare, M. H., Camps-Arbestain, M. (2018). Management practices to reduce losses or increase soil carbon stocks in temperate grazed grasslands: New Zealand as a case study. Agriculture, Ecosystems and Environment, 265:432-443. https://doi.org/10.1016/j.agee.2018.06.022.

## 9.5. Agroforestry

Abbas, F., Hammad, H. M., Fahad, S., Cerdà, A., Rizwan, M., Farhad, W., Ehsan, S., & Bakhat, H. F. (2017). Agroforestry: a sustainable environmental practice for carbon sequestration under the climate change scenarios—a review. Environmental Science And Pollution Research, 24(12), 11177-11191. https://doi.org/10.1007/s11356-017-8687-0

Baah-Acheamfour, M., Carlyle, C. N., Bork, E. W., & Chang, S. X. (2014). Trees increase soil carbon and its stability in three agroforestry systems in central Alberta, Canada. *Forest Ecology And Management*, *328*, 131-139. https://doi.org/10.1016/j.foreco.2014.05.031

Castle, S. E., Miller, D. C., Ordonez, P. J., Baylis, K., & Hughes, K. (2021). The impacts of agroforestry interventions on agricultural productivity, ecosystem services, and human well-being in low- and middle-income countries: A systematic review. Campbell Systematic Reviews, 17(2). https://doi.org/10.1002/cl2.1167

Graves, A. R., Burgess, P. J., Liagre, F., Pisanelli, A., Paris, P., Moreno, G., Bellido, M., Mayus, M., Postma, M., Schindler, B., Mantzanas, K., Papanastasis, V. P., & Dupraz, C. (2008). Farmer Perceptions of Silvoarable Systems in Seven European Countries. En Advances in agroforestry (pp. 67-86). https://doi.org/10.1007/978-1-4020-8272-6_4

López-Díaz, M., Benítez, R., & Moreno, G. (2017). How do management techniques affect carbon stock in intensive hardwood plantations? Forest Ecology And Management, 389, 228-239. https://doi.org/10.1016/j.foreco.2016.11.048

Lorenz, K., & Lal, R. (2014). Soil organic carbon sequestration in agroforestry systems. A review. Agronomy For Sustainable Development, 34(2), 443-454. https://doi.org/10.1007/s13593-014-0212-y

Makundi, W. R., & Sathaye, J. A. (2004). Mitigation potential and cost in tropical forestry - relative role for agroforestry. https://doi.org/10.2172/823930

Montagnini, F., & Nair, P. (2004). Carbon sequestration: An underexploited environmental benefit of agroforestry systems. Agroforestry Systems, 61-62(1-3), 281-295. https://doi.org/10.1023/b:agfo.0000029005.92691.79

Mosquera-Losada, M. R., Santos, M. G. S., Gonçalves, B., Ferreiro-Domínguez, N., Castro, M., Rigueiro-Rodríguez, A., González-Hernández, M. P., Fernández-Lorenzo, J. L., Romero-Franco, R., Aldrey-Vázquez, J. A., Sobrino, C. C., García-Berrios, J. J., & Santiago-Freijanes, J. J. (2023). Policy challenges for agroforestry implementation in Europe. Frontiers In Forests And Global Change, 6. https://doi.org/10.3389/ffgc.2023.1127601

Mutuo, P. K., Cadisch, G., Albrecht, A., Palm, C. A., & Verchot, L. (2005). Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. Nutrient Cycling In Agroecosystems, 71(1), 43-54. https://doi.org/10.1007/s10705-004-5285-6

Nair, P. K. R., Kumar, B. M., & Nair, V. D. (2009). Agroforestry as a strategy for carbon sequestration. Journal Of Plant Nutrition And Soil Science, 172(1), 10-23. https://doi.org/10.1002/jpln.200800030

Nair, P. K. R. (2011). Carbon sequestration studies in agroforestry systems: a reality-check. Agroforestry Systems, 86(2), 243-253. https://doi.org/10.1007/s10457-011-9434-z

Nath, A. J., Sileshi, G. W., Laskar, S. Y., Pathak, K., Reang, D., Nath, A., & Das, A. K. (2021). Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. Journal Of Cleaner Production, 281, 124831. https://doi.org/10.1016/j.jclepro.2020.124831

Palma, J., Graves, A., Bunce, R., Burgess, P., De Filippi, R., Keesman, K., Van Keulen, H., Liagre, F., Mayus, M., Moreno, G., Reisner, Y., & Herzog, F. (2007). Modeling environmental benefits of silvoarable agroforestry in Europe. Agriculture Ecosystems & Environment, 119(3-4), 320-334. https://doi.org/10.1016/j.agee.2006.07.021

Palma, J., Graves, A., Burgess, P., Van Der Werf, W., & Herzog, F. (2007). Integrating environmental and economic performance to assess modern silvoarable agroforestry in Europe. Ecological Economics, 63(4), 759-767. https://doi.org/10.1016/j.ecolecon.2007.01.011

Pumariño, L., Sileshi, G. W., Gripenberg, S., Kaartinen, R., Barrios, E., Muchane, M. N., Midega, C., & Jonsson, M. (2015). Effects of agroforestry on pest, disease and weed control: A meta-analysis. Basic And Applied Ecology, 16(7), 573-582. https://doi.org/10.1016/j.baae.2015.08.006

Quinkenstein, A., Wöllecke, J., Böhm, C., Grünewald, H., Freese, D., Schneider, B. U., & Hüttl, R. F. (2009). Ecological benefits of the alley cropping agroforestry system in sensitive regions of Europe. Environmental Science & Policy, 12(8), 1112-1121. https://doi.org/10.1016/j.envsci.2009.08.008

Quinkenstein, A., Böhm, C., Da Silva Matos, E., Freese, D., & Hüttl, R. F. (2011). Assessing the Carbon Sequestration in Short Rotation Coppices of Robinia pseudoacacia L. on

Marginal Sites in Northeast Germany. En Advances in agroforestry (pp. 201-216). https://doi.org/10.1007/978-94-007-1630-8_11

Schoeneberger, M. M. (2008). Agroforestry: working trees for sequestering carbon on agricultural lands. Agroforestry Systems, 75(1), 27-37. https://doi.org/10.1007/s10457-008-9123-8

Shi, L., Feng, W., Xu, J., & Kuzyakov, Y. (2018). Agroforestry systems: Meta-analysis of soil carbon stocks, sequestration processes, and future potentials. Land Degradation And Development, 29(11), 3886-3897. https://doi.org/10.1002/ldr.3136

Staton, T., Walters, R. J., Smith, J., & Girling, R. D. (2019). Evaluating the effects of integrating trees into temperate arable systems on pest control and pollination. Agricultural Systems, 176, 102676. https://doi.org/10.1016/j.agsy.2019.102676

De Stefano, A., & Jacobson, M. G. (2017). Soil carbon sequestration in agroforestry systems: a meta-analysis. Agroforestry Systems. https://doi.org/10.1007/s10457-017-0147-9

Visscher, A. M., Meli, P., Fonte, S. J., Bonari, G., Zerbe, S., & Wellstein, C. (2023). Agroforestry enhances biological activity, diversity and soil-based ecosystem functions in mountain agroecosystems of Latin America: A meta-analysis. Global Change Biology, 30(1). https://doi.org/10.1111/gcb.17036

Udawatta, R. P., Rankoth, L., & Jose, S. (2019). Agroforestry and Biodiversity. Sustainability, 11(10), 2879. https://doi.org/10.3390/su11102879

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

# 10. Annexes

## 10.1. Woody crops

**Annex 1A**. Keywords and connectors used for the search for the other three woody crops subsystems (olive groves, fruit orchards and almond).

**Olive groves**

Carbon sequestration in olive groves/Carbon sequestration and olive groves
Carbon farming and olive groves/ Carbon farming in olive groves
Nature based climate solutions in olive groves
Agro-environmental practices and organic carbon and olive groves
Carbon sequestration and olive groves and sustainable practices/ Sustainable practices and carbon sequestration and olive groves/ Organic carbon and sustainable practices and olive groves/ Sustainable practices and olive groves and carbon/ Sustainable practices and olive groves
Cover crops and carbon sequestration and olive groves/ Cover crops and carbon and olive groves
Pruning residues and carbon and olive groves/ Pruning residues and carbon sequestration and olive groves
Compost and carbon sequestration and olive groves/ Compost and carbon and olive groves/ Alperujo and compost and olive groves and carbon/ Alperujo and olive groves and carbon
Tillage and carbon sequestration and olive groves/ Tillage and carbon and olive groves
Emissions and olive groves and management practices/Emissions and carbon sequestration and olive groves/ Warming potential and carbon sequestration and olive groves

**Fruit orchards**

Carbon sequestration in fruit orchards/ Carbon sequestration and fruit orchards
Carbon farming and fruit orchards/ Carbon farming in fruit orchards
Nature based climate solutions in fruit orchards
Agro-environmental practices and organic carbon and fruit orchards
Carbon sequestration and fruit orchards and sustainable practices/ Sustainable practices and carbon sequestration and fruit orchards/ Organic carbon and sustainable practices and fruit orchards/ Sustainable practices and fruit orchards and carbon/ Sustainable practices and fruit orchards/ Organic carbon and fruit orchard and sustainable practices
Cover crops and carbon sequestration and fruit orchards/ Cover crops and carbon and fruit orchards


Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

Pruning residues and carbon and fruit orchards/ Pruning residues and carbon sequestration and fruit orchards
Compost and carbon sequestration and fruit orchards/ Compost and carbon and fruit orchards
tillage and carbon sequestration and fruit orchards/ Tillage and carbon and fruit orchards
Emissions and fruit orchards and management practices/ Emissions and carbon sequestration and fruit orchards/ Warming potential and carbon sequestration and fruit orchards
Citrus orchards and compost and carbon sequestration
Citrus orchards and pruning residues and carbon sequestration
Citrus orchards and cover crops and carbon sequestration
Citrus orchards and tillage and carbon sequestration
Peaches orchards and compost and carbon sequestration
Peaches orchards and pruning residues and carbon sequestration
Peaches orchards and cover crops and carbon sequestration
Peaches orchards and tillage and carbon sequestration
Apple orchards and compost and carbon sequestration
Apple orchards and pruning residues and carbon sequestration
Apple orchards and cover crops and carbon sequestration
Apple orchards and tillage and carbon sequestration
Kiwi orchards and compost and carbon sequestration
Kiwi orchards and pruning residues and carbon sequestration
Kiwi orchards and cover crops and carbon sequestration
Kiwi orchards and tillage and carbon sequestration
Nectarine orchards and compost and carbon sequestration
Nectarine orchards and pruning residues and carbon sequestration
Nectarine orchards and cover crops and carbon sequestration
Nectarine orchards and tillage and carbon sequestration
Carbon sequestration and sustainable practices and kiwi orchards
Carbon sequestration and sustainable practices and citrus orchards
Carbon sequestration and sustainable practices and apple orchards
Carbon sequestration and sustainable practices and nectarine orchards
Carbon sequestration and citrus
Carbon sequestration and peach
Carbon sequestration and apple
Carbon sequestration and nectarine

**Almond**

Carbon sequestration in almond/ carbon sequestration and almond
Carbon farming and almond/ carbon farming in almond
Nature based climate solutions in almond

Agro-environmental practices and organic carbon and almond

Carbon sequestration and almond and sustainable practices/ Sustainable practices and carbon sequestration and almond/ Organic carbon and sustainable practices and almond/ Sustainable practices and almond and carbon/ Sustainable practices and almond

Cover crops and carbon sequestration and almond/ Cover crops and carbon and almond

Pruning residues and carbon and almond/ Pruning residues and carbon sequestration and almond

Compost and carbon sequestration and almond/ Compost and carbon and almond

Tillage and carbon sequestration and almond/ Tillage and carbon and almond

Emissions and almond and management practices/ Emissions and carbon sequestration and almond/ Warming potential and carbon sequestration and almond

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

**Annex 1B**. Existing articles on aboveground and belowground biomass for subsystems (olive groves, vineyards, almond trees and fruit orchards) and for selected articles. For more information, the articles listed in the table are in the references section.

| Woody crop | Authors | Title of the article |
|---|---|---|
| **Olive groves** | López-Bellido et al., 2016 | Assessment of carbon sequestration and the carbon footprint in olive groves in Southern Spain |
| | Proietti et al., 2016 | Assessment of carbon balance in intensive and extensive tree cultivation systems for oak, olive, poplar and walnut plantation |
| | Proietti et al., 2014 | Carbon footprint of an olive tree grove |
| | Torrús-Castillo et al., 2023 | Does olive cultivation sequester carbon?: Carbon balance along a C input gradient |
| **Vineyards** | Callesen et al., 2023 | Understanding carbon sequestration, allocation, and ecosystem storage in a grassed vineyard |
| | Wong et al., 2023 | Short-term effects of increasing compost application rates on soil C and greenhouse gas ($N_2O$ and $CO_2$) emissions in a California central coast vineyard |
| | Lazcano et al., 2022 | Assessing the short-term effects of no-till on crop yield, greenhouse gas emissions, and soil C and N pools in a cover-cropped, biodynamic mediterranean vineyard |
| | Zumkeller et al., 2022 | Site characteristics determine the effectiveness of tillage and cover crops on the net ecosystem carbon balance in California vineyard agroecosystems |
| | Litskas et al., 2022 | Use of winery and animal waste as fertilisers to achieve climate neutrality in non-irrigated viticulture |
| | Sharifi and Hajiaghaei-Kamrani, 2023 | Biochar-compost mixture and cover crop effects on soil carbon and nitrogen dynamics, yield, and fruit quality in an irrigated vineyard |
| | Steenwerth and Belina, 2008 | Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem |
| | Song et al., 2023 | A Simple method using an allometric model to quantify the carbon sequestration capacity in vineyards |
| | Pitacco and Meggio, 2015 | Carbon budget of the vineyard - A new feature of sustainability |
| | Morandé et al., 2017 | From berries to blocks: carbon stock quantification of a California vineyard. |
| | Wolff et al., 2018 | Minimum tillage of a cover crop lowers net GWP and sequesters soil carbon in a California vineyard |
| | Brunori et al., 2016 | Sustainable viticulture: The carbon-sink function of the vineyard agro-ecosystem |
| | Keightley, 2011 | Applying new methods for estimating in vivo vineyard carbon storage |
| | Morlat and Chaussod, 2008 | Long-Term additions of organic amendments in a Loire Valley vineyard on a calcareous sandy soil. II. Effects on root system, growth, grape yield, and foliar nutrient status of a cabernet franc vine |
| | Vendrame et al., 2019 | Study of the carbon budget of a temperate-climate vineyard: Inter-annual variability of $CO_2$ Flux |
| **Fruit orchards** | Liguori et al., 2009 | Evaluating carbon fluxes in orange orchards in relation to planting density |
| | Baldi et al., 2018 | Effect of compost application on the dynamics of carbon in a nectarine orchard ecosystem |

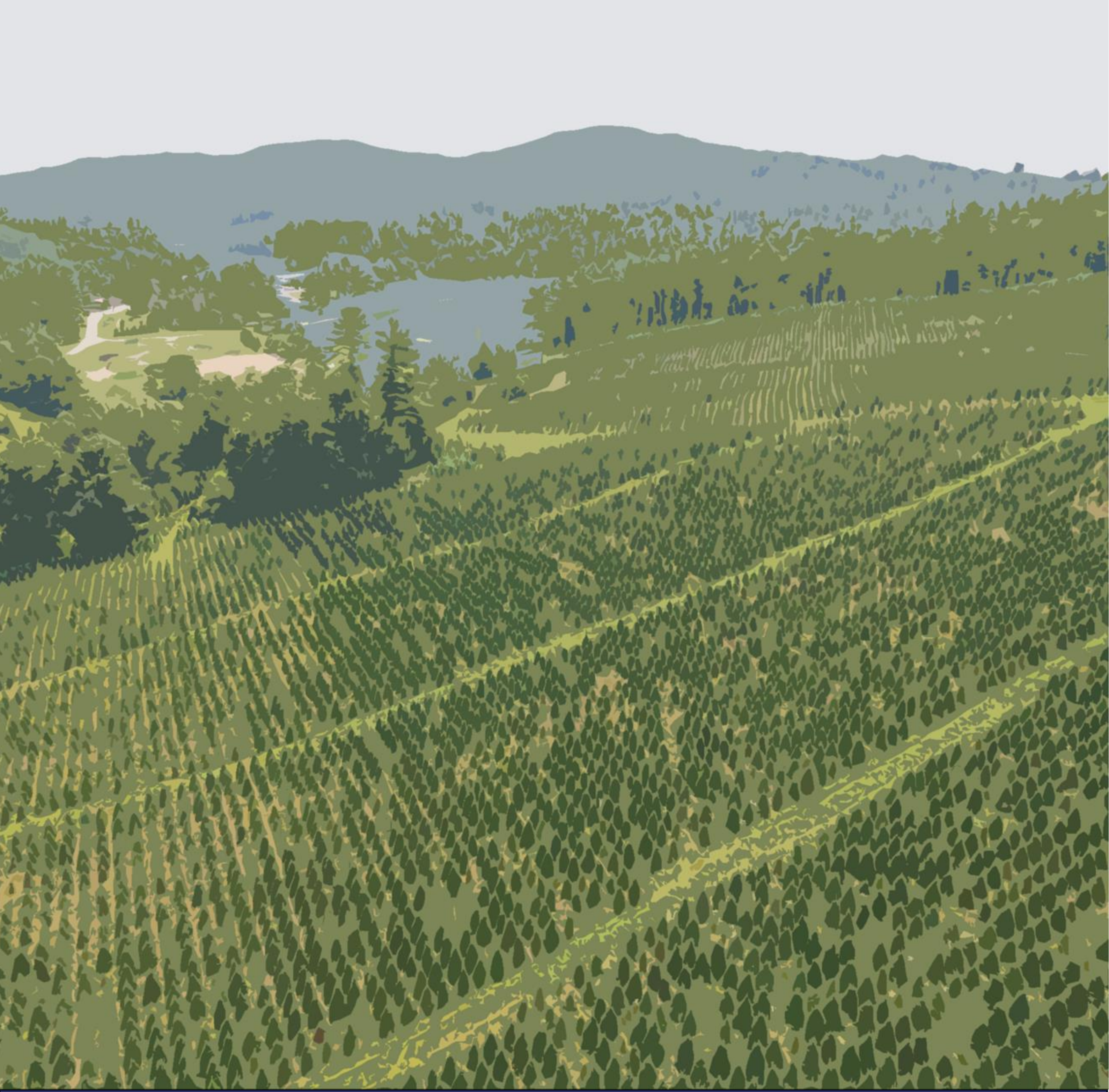
Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942

| | | |
|---|---|---|
| | Scandellari et al., 2016 | A survey of carbon sequestration potential of orchards and vineyards in Italy |
| | Zhao et al., 2015 | Effects of plantation ages, densities and management strategies on carbon sequestration in tropical mango and wax apple orchards ecosystems |
| **Almond trees** | Rubio-Asensio et al., 2022 | Effects of cover crops and drip fertigation regime in a young almond agroecosystem |
| | Almagro et al., 2017 | The potential of reducing tillage frequency and incorporating plant residues as a strategy for climate change mitigation in semiarid Mediterranean agroecosystems |

## 10.2. List of articles found in the search and database of variables

In ZENODO (10.5281/zenodo.14408832), different Excel sheets are available for each system considered, containing lists of articles described in the different sections. These correspond to the methodology for information search, along with their quantitative and qualitative details. The databases include all articles with some quantitative information, regardless of whether they have been used (or not) in result sections.

Project MARVIC has received funding from the Horizon Europe Programme under grant agreement no. 101112942



MARVIC

MRV for carbon farming

Funded by
the European Union