Carbon Sequestration and Agro-forestry

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D egrading agroforestry systems have the potential to store large amounts of carbon if they are properly maintained. The most common C pool considered in studies of soil C status changes in these ecosystems is labile C. Alterations to land use and soil management influence the proportion of soil organic matter that is easily decomposed to that which is more stable (SOM). The effects of land use on soil C storage over the long term can only be understood by analyzing stable C pools. The SOM's subsequent interaction with minerals and incorporation into soil aggregates both contribute to the SOM's stability. Substituting stubborn compounds for the inert SOM fraction (like lignin and chitin). Macroaggregates reflect the influence of plant roots and coarse intra-aggregate particulate SOM (POM) more so than the effects of fine inter-aggregate POM, clay concentration, and humified SOM percentage. It is often the case that precipitable organic matter (POM) is more sensitive to alterations in soil management than total SOM. Mycorrhizal fungi produce a chitin-based protein called global in to shield their hyphae. Further study is needed before any conclusions can be reached about the impact of glomalin on C sequestration in agroforestry soils. Roots' CO_2 output must be lowered, and stubborn root C must be fortified, to name only two of the many difficulties.

Keywords: Carbon Reserves, Organic Matter, Soil nutrients

Introduction

Because of human interference, the world's carbon (C) cycle has been disrupted, which has a chilling effect on the planet's climate. Rising levels of carbon dioxide in the atmosphere are a major factor in recent climatic changes on Earth (CO2) [1]. Soil organic carbon (SOM), which includes decayed plant matter and litter on the surface, is roughly three times as abundant as C in the air. As soil carbon accumulation can partially offset the effect of anthropogenic CO2 release, it is an essential strategy for lowering greenhouse gas emissions (GHG) [2]. Soil C storage is largely determined by both environmental (such as temperature and precipitation) and biotic (such as bacteria and fungi) factors (plant species and composition and anthropogenic activities) [3].

The following associations between soil organic carbon (SOC) concentration and various forms of land use have been discovered by researchers: Forests are preferable to orchards and agroforests to agriculture fields when comparing various tree plantations. Agroforestry systems that are created on agricultural land have a beneficial impact on SOC as opposed to those that are created on secondary or primary forests, which have a negative impact. [4]. The strategy used to consider the vast differences in C sequestration in soils between land uses, in addition to the biophysical and socioeconomic features of the system's parameters. Afforestation and replanting within the agroforestry system have been identified by the LULUCF as carbon sequestration activities. The Intergovernmental Panel on Climate

Change estimates that by 2040, agroforestry may sequester 586,000 t C yr1 by converting 630 million ha of underutilized croplands around the world. [5]. Nair noted, however, that there is a severe lack of rigorous data on C sequestration in these systems [6]. Basic information is necessary to assess changes in SOC stock and storage/loss after a LUC, including the description of the prior land use, SOC stocks or concentrations and bulk densities in both the former and new land uses, soil depth studied, and time since conversion. SOC may see a sharp drop after LUC, and it may take weeks or months for SOC to recover [7]. Accurate estimates of SOC changes in agroforestry systems are more challenging to make than in other land uses because the cultivation of various plant species and the dispersion of trees create varied gradients in organic inputs to the soil. Few research has looked at SOC storage in the subsurface layers of agroforestry systems. [4][8][9].

Large areas of cropland in Europe, notably in the Mediterranean basin, have been abandoned and transformed into pastures, including agroforestry systems, in recent decades with the goal of reducing the agricultural output surplus and enhancing the soils' ability to store carbon. A secondary succession of vegetation developed when the land was abandoned, with pasture colonization having a significant impact on SOC [10]. An estimated 50-60 t C ha1 could be stored in permanent pastures in agroforestry systems[11]. However, when annual benefits reach a quasi-equilibrium, the soil's capacity to sequester C (sink saturation) is near its limit (steady state). Because the soil's physicochemical properties define a threshold at which the available C storage niches are filled (a phenomenon known as C saturation), the researcher found that it is highly improbable that all ancient C in soils can be physically protected [12][13]. According to the researcher, a mechanistic explanation of a saturation level for unprotected and biochemically protected pools is urgently needed. The International Panel on Climate Change (IPCC) recommended including soil C sequestration in national GHG inventories over a minimum 20-year time period to account for this.

The goals of this review included, but were not limited to, the following: (1) determining the potential contribution of belowground plant tissue to C stock in agroforestry soils; (2) discussing land use strategies in Mediterranean environments to increase C sinks by the contribution of agroforestry systems; (3) determining the terminology and context in which each concept is used; and (4) addressing new approaches. [14][15].

Incorrectly, "C sequestration" is often used to refer to the annual accumulation of carbon in soil (stock). The percentage form is preferred when reporting the latter (mass per unit of area and time). The total amount of soil C includes both the inert OM pool and the labile (active) OM fraction. The labile fraction of SOM is more reactive to changes in soil management than the passive and recalcitrant fractions of OM [16][17]. The labile fraction, made up of residues from the partial decomposition, accounts for 20–50% of SOM in cold and semiarid regions but only 10–20% in tropical and subtropical zones. Therefore, in the next decade, the active pool would see the most turnover. After the first five years of management practice being put into place, Batjes claims that the concentration of SOM changes more slowly[18]. Soil C is sequestered because of the soil's passive (recalcitrant) and slow-release OM pools, which have meaningful residency periods of hundreds to thousands of years.

Both the "very slowly oxidized" (slow) pool of chemicals associated with macro aggregates and the "active" or "labile" pool of compounds rapidly oxidized from the fresh plant matter and microbial biomass are dominated by humic acid. [19][20][21].

SOM is physically protected in two ways: occlusion within aggregates and adsorption onto minerals. Because of their chemical stability and inaccessibility to soil microorganisms, SOM, humic acid, and humin are collectively referred to as "humic substances" [22]. Some

authors have argued against the validity of humic substances. For example, Lehmann and Kleber [23] argued that we should stop using terms like "humic substances" because they connote outmoded analytical techniques based on alkaline extraction of SOM fractions. Although some may argue against keeping them, Ponge [24] argued that they should be kept because of their utility in assessing the soil's contribution to ecosystem services. As a result, we don't have a definitive answer to this question [16]. The stability of stored SOM is more important than quantity in terms of soil C sequestration. More carbon is sequestered when C is chemically or physically stored in refractory compounds (such as chitin, cutin, and suberin) with a prolonged turnover, or a slow rate of disintegration (for example, when 2:1 clay mineral prevails in soil) (for example, inside the stable micro aggregates, forming organo-mineral complexes as secondary particles).

Furthermore described was a biochemically stable SOC pool with a century-plus turnover time[25]. The physically protected SOC pool's turnover period via occlusion in stable micro aggregates is greater than the unprotected, quickly degradable (free POM) SOC pool's turnover time (1–10 years), yet it is still shorter than the latter (10-100 years). As these authors noted, knowledge of the SOC fraction, which reflects the SOC's level of protection, is necessary to comprehend SOC dynamics in soil.

Since soils contain a sizable quantity of C already, the most elementary inquiry is about the C stock growth. While it is difficult to precisely assess changes in such a massive C pool, it is possible to utilize a subset of the total SOC as an indicator of C stock movement (whole SOC). Physically or chemically labile fractions, such as particle OM-POM, microbial biomass, and other pools, require specialized techniques that aren't routinely applied to as many samples as total soil C[26]. The top five centimeters of no-tilled silty loam soils have allegedly increased in POM by 100%, well exceeding the growth in total SOC (more than 30%).

Dry combustion (loss in ignition method) and wet oxidation total C measurements are inappropriate for assessing the components and dynamics of the soil C stock. [27]. (C sequestration). These methods are not only less effective, but they are also more hazardous to the environment and take more time. In addition, they do not differentiate between the volatile and the stable, as represented by humic substances and other stable organic compounds (nonlabile forms). Two non-destructive, cutting-edge technologies with significant potential for SOC monitoring in the field are nuclear magnetic resonance (NMR) spectroscopy and inelastic neutron scattering (INS), a technique in development. The structural characteristics of newly formed SOM, particularly in particular the POM in the sand section, can be used to identify them. This topic needs to be discussed in future C sequestration discussions.

Physical (particle size, aggregate size, or density) and chemical fractionation techniques, or a combination of the two, have been used to separate actively cycling (labile) SOM from more stable (recalcitrant) SOM. These methods can't completely isolate a single active fraction, even though they are only functional rather than truly functional. Both size and density can be used to distinguish between the two groupings. The stability-varying SOM fractions are isolated from the soil matrix using a high-density solution in the density fractionation method. Soil carbon is separated into light (>150 m) and heavy (150 m) fractions as a result (LF and HF, respectively). The POM and seeds, as well as microbial debris like fungal hyphal and spores, are good indicators of a labile fraction, which is largely comprised of younger plant debris that has only been partially decomposed[28]. The LF can be used as a precursor to SOM [29] because it is influenced by soil management. Late-stage amorphous material bound to soil minerals forms the HF fraction, which is rich in carbon. Soil C sequestration benefits more from HF than LF.

POM (both the coarse-sand-sized fraction (POM- CS) and the fine-sand-sized fraction (POM- FS)), coarse sand, fine sand, silt, clay, and POM are the final products of physical fractionation. The sand and coarser soil particles are where the soil's original organic content

was initially deposited (POM). Fine intra-aggregate POM (in the particle fraction of 50/53-250 m) is created when coarse intra-aggregate POM is physically and chemically broken. Both the rapidly degrading POM and the physically stabilized SOC make up this part of the OM. It's a transitional material between very fine sand and completely lifeless SOM. Once the fine intra-aggregate POM is coated with silt and clay particles and bonded by microbial products, very stable micro aggregates (50/53 m) are produced within the macroaggregates (2 mm) (e.g., glomalin, excreted by soil arbuscular mycorrhizal fungi). Long-term SOC storage and stabilization requires recalcitrant SOM that has been biochemically/protected. [30], which helps improve soil structure. The first stage of SOM conservation is similar to physical protection because both prevent mineralization by preventing microbes from accessing organic substrates and/or water and oxygen. Soil organic matter (SOM) is best shielded by the smallest soil aggregates because the energy needed to disrupt them is proportional to the square of their size. Low C sequestration in the soil can be caused by cultivation and other forms of soil disturbance. Then, the decline in aggregate stability is largely attributable to the disappearance of SOM.

Particulate organic matter (POM) is often cited as a stable SOM fraction; however, as has been reported elsewhere, POM is not stable enough to account for long-term changes in total SOM.

In a meta-analysis of the SMAF, the researcher included numerous multifunctional indicators, including critical soil functionalities (microbial carbon, acidity, phosphorus, and bulk density) (microbial carbon, acidity, phosphorus, and bulk density). Overall, they discovered that tillage lowered SOC levels by breaking up soil particles, speeding up mineralization rates (i.e. C oxidation), and leaving more of the soil vulnerable to wind and water erosion. Long-term, SOC depletion hampered soil biological activity, aggregate stability, water storage, incrusting surface crusting, and erosion. Keeping crop residues on the soil's surface and increasing SOM led them to the conclusion that switching from conventional tillage to no-till improved biological and physical indices of soil health in the topsoil. In conclusion, they suggested that switching from annual to perennial cropping could lead to long-term benefits in agroecosystem sustainability, environmental protection, and resilience to climate change.

To better understand SOM pool sizes and the changes that will occur as a result of management systems, accurate measurements may be of tremendous value to policymakers and C credit dealers. Modeling can be used to take these sorts of measurements (see, for example, the Q model, which excels in the face of varying climates; the Roth C model, in which "DPM" stands in for decaying plant matter and "BIO" stands in for biomass pools and simulates long-term physical protection; and the Century model, in which the metabolic compounds are linked to the "active" and "metabolic" pools) (see, for example, the Q model, which excels in the face of varying climates; the Roth C model, in which "DPM" stands in for decaying plant matter and "BIO" stands in for biomass pools and simulates long-term physical protection; and the Century model, in which the metabolic compounds are linked to the "active" and "metabolic" pools). However, successful modeling requires a large number of on-site measurements at designated sites to ensure accuracy[31]. More research is needed on soil sampling and analysis techniques. Developing non-destructive techniques would likely be of great importance for this goal.

Third, carbon (C) sink expansion via land use strategies in the Mediterranean region: Added Value of Agroforestry By using perennial crops and management techniques like no-tilling, residue mulching, extended crop rotation, and cover cropping, strategies may help reduce agricultural greenhouse gas emissions in Mediterranean regions. Agroforestry systems offer a very high potential for carbon sequestration because they include many of these CO_2 reduction techniques. However, there is a dearth of research on greenhouse gas (GHG)

emissions from agroforestry systems; taking into account other GHGs like methane (CH_4) and nitrous oxide (N_2O) is essential if we are to fully realize these systems' potential for climate change mitigation.

Trees (typically evergreens) and crops (such as cereals) are grown side by side in an agroforestry system, a type of complex agroecosystem [32]. Trees and perennial pastures (either natural or artificially improved) are also common components of agroforestry systems. Various combinations of tree and crop species may be used in such systems, with the choice ultimately determined by the local climate. Even beyond their ability to sequester carbon, these ecosystem services have the potential to increase soil fertility, prevent soil erosion, increase biodiversity, and help to moderate climate change. These cropping systems are of interest to both developed and developing countries as a means of carbon sequestration. Farmers in industrialized countries benefit from the increased productivity of these ecosystems as a result of the adoption of agricultural practices that boost C sequestration, and they receive compensation for C sequestration in the agroforestry systems based on the amount of C sequestered and the market price.

Trees, shrubs, and perennial grasses are utilized in agroforestry in order to cut down on greenhouse gas production. A stable collection of organic matter (OM) in the soil known as soil carbon storage acts as a stand-in for the atmospheric carbon dioxide removal process brought on by crop photosynthesis (C capture) and subsequent deposition in sinks (C storage). The capacity of these systems' soils and biomass to store carbon is influenced by a number of factors, including climate, land use, tree density, plant species, age, and management methods. Most investigations showed that SOC in deeper layers and the comparatively consistent soil C were acquired from tree components in tree-based pasture systems as opposed to pasture/grassland systems without trees (C3 plants).

Throughout the Iberian Peninsula of Southern Europe, there are important agroforestry systems known as "montado" in Portugal and "dehesa" in Spain. Grazing animals (sheep, black pigs, and cattle), typically in a rotation scheme, and repeated cereal cropping occupy the spaces between multipurpose trees like chestnut (Castanea spp.), oak (Quercus spp.), and olive (Olea europaea) trees (Olea europa L.). On around 4 million acres, this is done in Portugal and Central and Southwest Spain. Both in Europe as a whole and in the Mediterranean region, this practice has a long history.

Related Studies.

Due to low soil fertility, shallow soil depth, and limited water and nutrient availability, natural pastures in the Mediterranean are typical of low productivity and quality. Farmers on the Iberian Peninsula, alarmed by the low productivity of pastures, sowed legume-rich mixture pastures [33], which increased pasture productivity and SOC concentration at the same time and halted soil degradation. Even though improved pastures can maintain high productivity for more than 20 years with the right amount of grazing and fertilization, there are no studies that definitively state how best to manage improved pastures to ensure their longevity.

Similarly to trees, permanent pastures (both natural and improved) can rapidly increase soil C for three main reasons: first, the presence of perennial species that grow continuously rather than seasonally with extensive root systems; second, the minimal soil disturbance relative to arable crops or annual pastures; and third, the facilitation of the diversity and activity of soil organisms, which promotes soil aggregation and, thus, C p. Carbon sequestration through the management of degraded pastures has a high potential, but quantifying this potential in the field is difficult due to a lack of data from mature and stable ecosystems.

Distributed tree plantings enhance soil fertility and the physical and biological health of the soil in their shade, as shown by analyses of spatial heterogeneity in soil C at the tree level in these agroforestry systems. The 0-10 cm soil layer under the tree canopy in both natural (2.4 kg C m2) and improved (3.1 kg C m2) Spanish pastures had significantly more organic C

than the open field (1.8 and 2.1 kg C m2, respectively). Research shows that the amount of root litter produced in the topsoil layer and the amount of organic litterfall residue deposited annually both have a direct correlation with the amount of SOC found in the soil below a forest's canopy. When one moved away from the main trunk, the variation became less pronounced. In fact, Simón et al. found a positive correlation between tree cover and SOC stocks out to distances of 8 meters from tree canopies. However, the study found that trees had a major impact on the SOC concentration in the improved pastures, with a larger percentage in the soil beneath the tree canopy than in the open field. There was almost the same carbon-to-nitrogen ratio in pasture litter and city litter. Tree litterfall residues are more difficult to decompose than those from herbaceous plants because of the higher C/N ratio in the former. The study's author vouched that this percentage of organic carbon was the same as the percentage of OM that did not contain any particles [34]. Though no data are currently available, it is possible that plant matter from belowground sources contributes to the nonparticulate SOM. Soil organic carbon was estimated to be 2.3% in the top five centimeters of the highly variable woodland soils of southwestern Spain by Pulido-Fernández et al. Both the SOC concentration and variability fell with depth, though they were both greatest at the surface. Soil C storage is highest under tree canopies in Central and Western Spain, as found by the researcher who also discovered that dispersed trees in agroforestry systems strongly influenced spatial variability in SOC concentration. In terms of SOC sequestration potential, montados and dehesas have been underrepresented in large-scale studies, as stated by Simón et al. This is possibly due to their lackluster SOC content, their spatial heterogeneity, and/or the difficulty inherent in managing them. Pulido-Fernández et al. found 2.3% organic C in the top 5 cm of the highly variable soils of Southwestern Iberia. SOC concentration and variability decreased with depth but were both highest near the surface. The spatial variability of organic C concentration was also significantly influenced by the dispersed trees in the agroforestry systems, Howllet et al. found, with more carbon being stored in the soil directly under tree canopies. In terms of SOC sequestration potential, montados and dehesas have been underrepresented in large-scale studies, as stated by Simón et al. This is likely because of their low SOC contents, spatial heterogeneity, and complex management.

It is worth noting that the implementation of enhanced pastures may magnify the impact of dispersed trees on organic C accumulation in the topsoil. Soil organic C stock in a 26-year-old improved pasture was found to increase by 0.18 and 0.84 kg m2 in open and tree-covered areas, respectively, when compared to a natural pasture with shrub control every six years.

Due to the effects of trees on the understory, the C/N ratio in the topsoil of oak woodlands may be variable. This trend is in line with the research of the researcher who found that the C/N ratio decreased from 33 to 20 in areas with a tree and shrub understory and improved pastures, respectively. The difference may be explained by the fact that the C/N ratio of litterfall residues from trees is higher than that of herbaceous vegetation, making the former take longer to decompose. Furthermore, researchers [35] confirmed that the nonparticulate SOM fraction accounted for the vast majority (58-79%) of the organic C found beneath trees. Though no data are currently available, it is possible that plant matter from belowground sources contributes to the nonparticulate SOM [36].

The main reasons for agroforestry's application in industrialized nations are its advantages for the environment and economy. The Portuguese government has been providing financial incentives to farmers through the Portuguese Carbon Fund since 2009 to repair degraded pastures across a total area of 42,000 hectares with the aim of accumulating EUR 0.91 million of CO2eq between 2010 and 2012. Farmers were able to offer this service for a fair price by using a "biodiverse permanent pasture method, rich in legumes". Stocking rates were closely observed after no-till sowing of rainfed pastures with a mixture of legumes

and nonlegumes (up to twenty different species and cultivars, including species with high-self-reseeding capacity and species able to establish deep roots to deal with cattle pressure and long dry summers). Over a five-year period, it was predicted that this pasture management will increase SOM by 0.2% yr-1 on 80 Portuguese farms, which is comparable to adding 5 t CO2eq ha1 yr-1 of CO2.

When comparing Australia's extensive grazing pastures to its dairy pastures, the latter were found to have significantly lower SOC concentrations in the top 10 centimeters of their soils (3-7%). McKenzie and Watson [37] cite an article by Watson (2010) titled "Portugal gives green light to pasture carbon farming as a recognized offset" to demonstrate the technique's applicability to Australian managers of degraded land, where livestock grazing could generate carbon credits for farmers [34].

It's generally agreed that plant nutrition plays a significant role in determining how plants and ecosystems will react to changes in atmospheric CO2 levels. C3 plants react more quickly than C4 plants to rising CO2 levels in the atmosphere. Comparatively, most grasses are C4 plants while legumes are C3. On the other hand, C4 grasses in tropical and temperate pastures can store a lot of carbon. McSherry and Ritchie claim that C4 grasses' greater root-to-shoot ratio allows for greater transfer of photosynthates belowground, greater root density and turnover, and possibly greater root exudates, all of which contribute to a greater SOC yield. Root characteristics that influence nutrient uptake and their response to high CO2 concentration are important to know if one is to accurately predict the long-term plant and ecosystem response to CO2 enrichment [38][39].

Both the number of tree species used and the nature of their combinations can affect the amount and quality of biomass returned to the soil through an agroforestry system. Root growth, decay, and turnover are poorly understood, despite the fact that the contribution of belowground plant biomass to soil C pools (labile or stable) is attracting considerable interest in the specific context of GHG mitigation. Because of this, data on the carbon stocks of subterranean plant parts are uncommonly reported, and when they are, they lack credibility due to a lack of scientific rigor [40][38][39].

In pasture crops, the plant can use up to 50% of the carbon (C) it absorbs to construct its underground tissues. In temperate pastures, the amount of NPP reaching the soil is variable, ranging from 24 to 87 percent. Root C lost through respiration (20-40% of that imported) is primarily used for plant growth and ion uptake, but there are also significant fluxes to symbionts, perhaps 10-27% to mycorrhizal fungi. Clearly, there is a huge potential for SOM and C sequestration by roots and mycorrhizal hyphae. Some of the carbon released by decomposing roots is converted to carbon dioxide, while the rest is stored in the soil as organic matter (SOM). Reducing carbon dioxide emissions from roots while increasing the amount of carbon from roots that refuse to contribute to the stable SOM pool is a real challenge.

Soils in warm and arid regions, like the Mediterranean, store less SOC than soils in cool and humid regions because of the higher air temperature and lower rainfall. Only at temperatures between 25 and 30 degrees Celsius does SOM decompose to a significant degree. Comparatively, fine-root decomposition is more temperature-dependent than the decomposition of leaf litter [36][34][41]. When compared to the Q10 of 2.36 for leaf litter, which indicates a dramatic increase in mass loss with increasing temperatures, the Q10 of 4.2 for extremely fine roots (0.5 mm) is striking. Bonanomi et al. state that lignin and (low) N concentration strongly limit decomposition at low temperatures (e.g., 4 C) but weakly limit it at high temperatures (e.g., 24 C). The enzymes required to degrade lignin are thought to be less efficient at lower temperatures. Fine root renewal in pastures was found to increase exponentially with rising temperatures by Norby and Jackson, but not to be influenced by changes in precipitation. The authors Gabarrón-Galeote et al. compared C stocks at three sites following land abandonment. The Rock of Gibraltar is situated in the southern region of

Europe. Gains in SOC were highest (59.8%) in the fine fraction (50/53 m) and lowest (19.4%) in the intermediate fraction (50-250 m) in both wetter and semiarid regions. As a result, we can see that precipitation has a tangible effect on C sequestration [42][3][1].

In the olive agro-forestry in Andalusia, Spain, temporary spontaneous cover crops grown above ground have the capacity to fix around 1.5 t of SOC per hectare year, culminating in a store of 16 t ha1 over a 10- to 30-year period. In other words, olive trees could achieve their goals of lowering their CO2 emissions if they used the same strategy. French researchers found that an agroforestry system with a mean age of 17.8 years can store 0.24 t C ha1 yr1 of carbon dioxide. The Mediterranean's C stocks are particularly vulnerable to climate warming. According to the authors, the intermediate fraction of SOM and the most stable fraction of SOM will be most affected by the anticipated rise in temperature and decrease in rainfall. Particle-size-sorted organic matter (POM), which was unaffected by precipitation, dominated the coarse fraction (>250 m) of OM. In this study, we discovered that whereas SOC bound to mineral particles was impacted by precipitation, POM was unaffected by changes in land use. Recent research on LULUC variations in the Bragança region of northeastern Portugal (latitude 41.9893° to 41.7691°, longitude 6.5747° to 6.82292) has shown that these variations have a positive impact on carbon storage and sequestration. Total C storage increased by 49.2% at a rate of 1.5 t C ha1 yr1, according to the research. This is mostly due to agroforestry techniques expanding the amount of forest cover on agricultural soils with low SOC densities. Teixeira et al. discovered that although native pastures did not consistently exhibit an increase in SOM in the same climate, improved pastures under Portuguese agroforestry systems showed a significant increase in SOM following five years of land use change (2001-2005) in all cases examined (80). (average daily temperature of 15.5-16.8 C and annual precipitation of 200-750 mm) [29][17][44].

Root C inputs can be substantial, but they decrease dramatically with soil depth as root biomass decreases. Depending on how far the roots have penetrated, a lot of organic C can be stored below the plow layer, where it is less likely to be lost to erosion and has more time to accumulate. Some trees in agroforestry systems may benefit from this kind of organic C accumulation at depths greater than 60 centimeters [27][15][16].

The rate and amount of C sequestered in an ecosystem are both governed by the decomposition of plant litter, making it an essential process in global C cycling [22]. However, root decomposition and element release have received little attention, and there are only a small number of studies conducted in the Mediterranean. Roots with a diameter of less than 2.0 mm are thought to decay rapidly (within days to weeks), whereas lignified coarse roots and the larger and thicker hyphae of mycorrhizal fungi often decompose substantially more slowly and may therefore significantly contribute to C stocks. Fine roots (2 mm) only contribute 14-27% of NPP to the C pool in an ecosystem due to their short lifespan. Extremely fine tree roots, such as those of pine trees (0.5 mm), degrade more slowly than thicker (0.5-2.0 mm) roots or aboveground litter from the same plant species [15][24].

Researchers all discovered that the stoichiometry of fine root decomposition rates correlated strongly with one another, but that C quality was the primary regulator of root decomposition. For instance, in a number of herbaceous plant species native to the Mediterranean region, the potential decomposition rates of fine roots (2.0 mm) were positively correlated with the concentration of soluble compounds, while cellulose concentration was inversely correlated. Fun and Guo hypothesize that fine tree roots, specifically the first- and second-order roots, will decompose more quickly than higher-order woody roots. However, this prediction has not been confirmed and may be off. Lower-order roots in tree species associated with ectomycorrhizal fungi may decay more slowly than higher-order roots due to preferential colonization by fungi and encasing in a fungal sheath rich in chitin (a recalcitrant compound). Sun et al. noted that the C/N ratio is lower in lower-order roots, particularly those

of trees. However, they confirmed that in low-N soil, both arbuscular mycorrhizal and ectomycorrhizal tree roots decomposed more slowly than higher-order roots [23][14][44]. The entire nonstructural carbohydrate content (sugars and starch) of extremely fine roots (0.5 mm) rapidly vanished during the first eighty-two days of decomposition, to be replaced by the acid-hydrolyzable carbohydrate component (cellulose and hemicellulose) (lignin, cutin, suberin, and other aliphatic compounds). In both the early and late stages of decomposition, very thin roots (0.5 mm) deteriorated more slowly than larger roots (0.5-2.0 mm), the study found. According to Sun et al., this is caused by a combination of a lower initial N content in the roots and a higher proportion of acid-nonhydrolyzable carbohydrate fraction [44][45] [46]. Researchers discovered that acid-nonhydrolyzable carbohydrate concentrations correlate well with decomposition rates. Investigators discovered that microbial N starvation can be exacerbated when very fine roots (0.5 mm) decompose in nutrient-poor soils because this nutrient is rapidly depleted during the decomposition process. More specifically, the investigator found that immobilization of N occurs early in the decomposition process in low-N soils, where microorganisms rely on soil N after tissue N is gone [47] [48]. Researchers found that fine roots high in energy-C compounds but low in inhibitory compounds decompose more quickly. Researchers found that the quality of root litter was more heavily influenced by its composition (stoichiometry) than by its initial root litter [13][49]. More research with a wider range of plant species, under field conditions, and over longer periods of time is needed to confirm these results and clarify the underlying mechanisms. Despite the fact that the IPCC tier 1 level calculation only accounts for a reference soil depth of 30 cm, it has been shown that deeper layers should be considered when calculating SOC stock changes [45][44].

Results and Discussions.

There may be as many as 50% arbuscular mycorrhizal fungi (AMF) in soils, according to some calculations [50]. AMF are symbiotic microorganisms that live in close proximity to many plant species, including 80 percent of cultivated plants. Although widespread, this symbiosis is somewhat species-specific; it enhances plant health and productivity in the face of a wide range of adverse conditions, including drought, high temperature, salinity, depleted nutrients, and contaminants like heavy metals [45][44][51]. Mycorrhizal plants increase atmospheric C sequestration in soil by exuding more photoassimilates into the soil through their roots, thanks to increased photosynthetic CO_2 uptake (mitigation). Both natural and cultivated ecosystems show a wide range of hyphal morphology (including wall thickness, width, branching patterns, and turnover), function (including nutrient absorption, plant protection, and soil aggregate formation and stabilization), and longevity due to differences in the mycorrhizosphere. Based on their architecture and wall thickness, Nichols identified two distinct morphologies of extraradical hyphae: (i) larger and thicker, more melanized hyphae that are a part of the "permanent" fungal network and act as "conduit" or "runner" hyphae, and (ii) thin-walled, very fine, ephemeral hyphae that are the "absorptive" hyphae. Turnover of "runner" hyphae, which takes years but ultimately contributes to C sequestration in soil, is a key factor in this process, as stated by the author [52][4][54]. Although root decomposition is affected by mycorrhizal association, specifically arbuscular, ectomycorrhizal, and ericoid mycorrhizal fungi (AMF), its effects have not been thoroughly investigated, especially in pasture species [54].

Due to the effects of climate change (increased atmospheric CO_2 concentration and temperature), plants will grow in size, necessitating deeper root systems. However, C partitioning to these plants will not change significantly. The soil's water and nutrient supplies could be depleted if these larger plants were allowed to grow there. This is possible in Mediterranean agroforestry systems. Therefore, the number of (mycorrhized) roots will increase at the expense of the number of (unmycorrhized) shoots. If soil nutrients are depleted, roots may exude more fluid and transfer more carbon (C) to mycorrhiza and soil. Particularly

vulnerable to the effects of climate change on mycorrhizal functioning is the amount of carbon that is transferred to and stored in the soil. It has been found that C4 grasses in pastures are more likely to have their roots colonized by mycorrhizal fungi than C3 grasses [55][56][57][58]. The variation in SOC between C3 and C4 grasses may have its origins in the different mycorrhizal associations between the two types of grasses. When considering the potential of low-input pastures for C sequestration in soil, especially in the presence of higher atmospheric CO2 concentration due to climate change, it is important to keep in mind that in permanent improved pastures in Mediterranean-type areas, strong competition of grasses and other no leguminous plants for soil water and nutrients may cause a great exudation and transfer of C into the soil. Several writers have observed that improved pastures have a greater effect on SOC buildup in wooded environments (such as the evergreen oak woodlands in southern Portugal) than in the open field. Still, academics haven't paid nearly enough attention to this issue.

Soil management and environmental factors in pastures have an impact on the types and numbers of AMFs found in the soil and the roots[59]. Mycorrhizal formation varies seasonally, the host plant's ability to supply the symbiont with photosynthetic products, and the timing, intensity, and duration of shoot removal (such as grazing) all play a role [60][9]. Due to their sensitivity to soil disturbance, the diversity of AMFs tends to increase when agricultural inputs are decreased. When grazing occurs, more of a substance called glomalin is excreted into the soil, which may encourage the growth of mycorrhizal hyphae.

There is a portion of the mycorrhizal hyphae mass in pastures that are composed of the recalcitrant compound (glomalin) formed by chitin, which may account for the stable SOM pool, lasting for years in the soil [61]. The glomalin produced by mycorrhizal fungi is a reddish-brown hydrophobic glycoprotein that is extremely stable (quite recalcitrant, containing 30-40% organic C) and insoluble in water and salt solutions typically used in soil extractions. Glomalin is an important source of soil carbon because of its role in preserving the stability of soil aggregates. The researcher notes that mycorrhizal (and saprophytic) fungi are the most important soil microorganisms for aggregate formation and stabilization. The researcher is deposited outside the hyphal walls of the extraradical mycelium and on adjacent soil particles, where it appears to act as a long-term soil cement agent contributing to the formation of micro aggregates[62]. This variation in aggregate formation among plant species is due to a number of factors, such as root size and colonization, plant nutrition, soil structure, and climate. Soil aggregation happens quickly as a result of AMF root colonization of soil. In a study conducted by Marcel et al., it was found that compared to microcosms without AMF, those inoculated with AMF formed 3.2% more aggregates (>1 mm). Before this molecule can be used as a precise assessment of soil quality and management impact on soil C sequestration, its concentration must be correlated with the long-term increase in aggregate stability. Large macroaggregates (>2 mm) increased dramatically from 10% in agricultural soil to 30% in afforested soil, showing a strong positive response of glomalin to land use change (Rillig et al., 2010). In spite of the need for more studies to confirm these results, glomalin shows promise as a sensitive indicator of soil C changes in response to land use practices.

The total biomass of AMF hyphae in soil, which has been estimated at 0.05-0.90 t C ha1, appears to be contributed by glomalin at a rate of 0.4%-6%. The glomalin in the hyphal wall is released into the soil when the hyphae senesce [63][64]. Glomalin C was estimated to contribute between 3.8% and 7.8% of the total SOC by Rillig et al., but this value varied greatly by land use and overall SOC (from agricultural to afforested and natural soils). About half of the glomalin was still detectable after incubation for 400 days at 25 C and 60% water-holding capacity, suggesting that half of this protein was in the labile fraction of the soil C pool and was lost during the first phase of decomposition. After accounting for ambient temperature, it was discovered that glomalin can have a much longer shelf life in the field than expected for

plant-derived proteins, with a mean residence time 2.67 times slower than reported. Rillig et al. [65] used 14C data from tropical forest soil and found that glomalin decays in 6–42 years.

Optimization of Carbon (C) Sequestration in Mediterranean Agroforestry Soils through Novel Approaches For agricultural ecosystem functions like lowering atmospheric CO_2 and maintaining a steady supply of food, feed, fiber, and energy for a growing human population to be maintained, suitable land use and management systems must be established in the Mediterranean agroforestry systems. The percentage of water-stable aggregates in the soil is raised by no-tillage practice and permanently improved pasture cultivation by increasing mycorrhizal hyphal length and microbial exudates in the mycorrhizosphere. Increased C sequestration is possible in no-tilled soils because C is allocated belowground to hyphal networks through the formation of highly stable glomalin, and the SOM occluded within aggregates appears to have a greater turnover time than the free SOM [66][65][67].

Conclusion

However, there are some challenges that are specific to permanent pastures and the mycorrhizal (i.e. glomalin) contribution to lowering atmospheric CO_2. Since C storage in pasture soils can be affected by mycorrhizal groups' growth rates and recalcitrant chitin content, more study of mycorrhizal physiology is needed before any prediction can be made. Ril- lig et al. found that the total glomalin concentration in agricultural, afforested, and natural soils decreased from horizon A to C, but little is known about the distribution of glomalin in agroforestry soil profiles. The reason for this is that the majority of studies focused on the upper layers (20-80 cm), where the largest C pools are not detected (mostly as labile SOM).

There is a lack of data on the stocks of organic C in the subsurface, where most tree roots are found, and where root exudates and fine-root turnover generate a significant C supply. The assessment of soil C for global change scenarios requires knowledge of C pools in the deeper layers of soil, which is especially relevant for Mediterranean agroforestry systems that incorporate both native and improved pastures. More study is also needed on the part of mycorrhizal systems in agroforestry systems, where pastures and trees interact, to determine how they can best improve the efficiency with which soil C is stored. The "biodiverse Portuguese technique," which involves the addition of phosphorus and the planting of productive pasture crops, sometimes in conjunction with bred plant legumes, is one of the most efficient ways to increase C stock. Guidelines for pastures with tree management in agroforestry systems can be established with this information in mind, resulting in greater ecosystem stability and service value for farmers and the general public.

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