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Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions?

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ABSTRACT

Climate change mitigation and food security are two of the main challenges of human society. Agroforestry systems, defined as the presence of trees on external and internal boundaries, cropland, or on any other available niche of farmland, can provide both climate change mitigation and food. There are several types of agroforestry systems with different rates of above ground and soil carbon (C) sequestration. The amount of carbon sequestered can depend on the type of system, climate, time since land use change and previous land use. Data was collected from a total of 86 published and peer reviewed studies on soil and above ground carbon sequestration for different agroforestry systems, climates and regions in the world. The objective was to understand which agroforestry systems provide the greatest benefits, and what are the main factors influencing, soil and above ground carbon sequestration. The results show that, on average, more soil carbon sequestration occurs in agroforestry systems classified as silvopastoral (4.38 tC ha^{-1} yr^{-1}), and more above ground carbon sequestration occurs in improved fallows (11.29 tC ha^{-1} yr^{-1}). On average, carbon benefits are greater in agroforestry systems Tropical climates when compared to agroforestry systems located in other climates, both in terms of soil (2.23 tC ha^{-1} yr^{-1}) and above ground (4.85 tC ha^{-1} yr^{-1}). In terms of land use change, the greatest above ground carbon sequestration (12.8 tC ha^{-1} yr^{-1}) occurs when degraded land is replaced by improved fallow and the greatest soil carbon sequestration (4.38 tC ha^{-1} yr^{-1}) results from the transition of a grassland system to a silvopastoral system. Time since the change is implemented was the main factor influencing above ground carbon sequestration, while climate mainly influences soil carbon sequestration most. The results of the analysis may be used to inform practitioners and policy makers on the most effective agroforestry system for carbon sequestration. The lack of data on carbon stocks before the implementation land use change and the lack of reporting on soil sampling design and variances were the main limitations in the data. The need to report this data should be considered in future studies if agroforestry systems are expected to play an important role as a climate change mitigation strategy.

1. Introduction

The relationship between land management and climate change has previously been identified across some of the key global agricultural systems (FAO, 2011a). The rural land use sector (forest, moorland, peatland, agriculture) has the unique capacity of delivering zero and negative carbon emissions since it can act as a sink and reservoir for carbon dioxide (Feliciano et al., 2013). Mitigation of climate change through increased carbon sequestration in the soil can be particularly useful when addressed in combination with other challenges that affect people's livelihoods, such as reverting land degradation and ensuring food security (Batjes, 2003). Potential increases in carbon sequestration may occur in agricultural and forest lands via improved land use management, conversion to land use with higher carbon storage, or increased carbon storage in harvested products (IPCC, 2000). Agroforestry systems provide options to mitigate climate change with the possibility of increasing in crop yields, and providing other positive environmental outcomes such as climate change adaptation (Tubiello et al., 2008; Smith et al., 2013; Mbow et al., 2014; Luedeling et al., 2014; Coulibaly et al., 2017; Waldron et al., 2017). In these systems, woody perennials (e.g. trees, shrubs, palms, bamboos) are cultivated in the same land-management unit with crops and/or animals, in some form of a spatial arrangement or a temporal sequence (Nair, 1993; Montero et al., 1998; Joffre et al., 1999). The diversification of the farm

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system into an agroforestry system can increase agricultural productivity, improve soil fertility, control erosion, conserve biodiversity, and diversify income for households and communities (Bishaw et al., 2013). Agroforestry systems are currently more common in temperate, sub-tropical and tropical zones, and include a wide range of land uses and practices (Torquebiau, 2000; Nair, 1985). In the tropics agroforestry systems are especially practised by smallholder farmers (Lorenz and Lal, 2014). According to FAO (2011a), there are five main forms of agroforestry, namely alley cropping, forest farming, silvopastoralism, riparian forest buffers, and windbreaks. These integrate technologies such as contour farming, multistorey cropping, intercropping, multiple cropping, bush and tree fallows, parkland, or homegardens. Other authors (e.g. Schoeneberger, 2009; Kandji et al., 2006) have also considered other nomenclatures, including agrisilvicultural systems, woodlots, boundary planting, lives fences, or multistrata agroforests. Agroforestry systems have received increased attention because of their capacity to sequester carbon dioxide from the atmosphere in above ground biomass, i.e., stems, branches, and foliage, and in below ground biomass, i.e. roots, and in the soil (Mutuo et al., 2005; Oke and Olatiilu, 2011; Nair, 2012; Lorenz and Lal, 2014). Carbon sequestration also represents an economic opportunity for subsistence farmers in developing countries if opportunities to sell carbon sequestered through agroforestry activities to industrialised countries become more widespread (Nair et al., 2009). Currently, payments for carbon sequestration are limited to voluntary carbon markets, but it is expected that emerging domestic legislation in several developed countries may soon increase the demand for emission reductions from land management activities (Lipper et al., 2010). According to Nair et al. (2009) there is currently an area of 1023 Mha under agroforestry worldwide, with a carbon sequestration potential of 1.9 PgC over 50 years. There is, therefore, substantial land area available on which agroforestry systems could potentially be deployed. (FAO, 2011b). It is therefore crucial to quantify the potential of these systems for carbon sequestration and climate change mitigation. Although the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) exist, these only cover potential carbon storage for agrisilvicultural and silvopastoral systems in dry lowlands and humid tropical regions (Dixon, 1995). There is a well-established body of literature on the potential of agroforestry systems for carbon sequestration, indicating a good understanding of the potential. However, this literature is very heterogeneous in methodology and purpose, and the potential benefits have not been systematically compared. Coarse estimates of the potential for above ground and soil carbon sequestration in agroforestry systems lack the refinement to enable the differential effects of important practice-related, or other contextual variables. According to Acin-Carrera et al. (2013), there are very few available studies that compare different land uses (e.g. agroforestry versus cropland) to evaluate how intensive or extensive uses impact on soil properties (e.g. soil carbon sequestration). Jose and Bardhan (2012) consider that if agroforestry is to be used in carbon sequestration schemes such as the clean development mechanisms, better information is required about above and below ground carbon stocks and soil carbon in areas under agroforestry systems. There is, thus, a need for estimates which are sensitive to specific regions, climates, and practice factors for agroforestry systems. Farmers, project planners, and project managers must be able to assess the likely benefit, including carbon sequestration potential, of agroforestry systems according to site circumstances.

The aim of this study is to provide an understanding of soil and above ground carbon sequestration in agroforestry systems with respect to region, climate, agroforestry type, and time of implementation. This study also aims at understanding the main factors influencing soil and above ground carbon sequestration. More specifically, the objectives of this study are to 1) identify agroforestry systems implemented in different regions of the globe; 2) quantify the sequestration potential of different agroforestry systems and; 3) understand the factors influencing carbon sequestration.

2. Methods

2.1. Data collection

The systematic literature search identified 40 peer reviewed studies that reported above ground carbon sequestration (date range 1984–2015) and 46 that reported soil carbon sequestration in agroforestry systems (date range 1995–2015) (Supplementary material) providing two independent databases. Peer reviewed studies were selected through the ISI-Web of Knowledge, Google Scholar, and Scopus. The searches were performed using several words related to agroforestry systems and carbon sequestration, more specifically agroforestry*OR land management practices*OR carbon sequestration*OR soil carbon sequestration*OR climate change*OR mitigation*OR above ground carbon sequestration (or the same terms in Spanish or Portuguese). The terms were used separately or in combination with each other. Both review articles and original studies were considered. The reference lists of the published reviews on the topic were also searched for eligible studies through snowballing. The articles with relevant titles were retrieved and the abstracts read. The studies selected for further reading and analysis were those that reported on:

1) Above ground carbon sequestration per year (MgC ha^{-1} yr^{-1}) or total carbon storage per hectare (MgC ha^{-1}) before and after implementation of the agroforestry system;
2) Soil carbon sequestration per year (MgC ha^{-1} yr^{-1}) or total carbon storage per hectare (MgC ha^{-1}) before and after implementation of the agroforestry system (covering soil carbon only and not tree roots);
3) Land use before and after the implementation of the agroforestry system;
4) Time since implementation of the agroforestry system (age of the agroforestry system in number of years);
5) Climate;
6) Country.

2.2. Data treatment

Depending on how data was reported, some adjustments had to be made. If only total carbon storage per hectare (MgC ha^{-1}) in soil or above ground was reported before and after implementation of the agroforestry system, both values were divided by the number of years since implementation to estimate carbon sequestration rates in MgC ha^{-1} yr^{-1}. Information on land-use before the implementation of the agroforestry system was often reported. For a few cases, land use before was inferred from careful reading of the section about the characteristics of the study site. Whenever this information was not reported or could not be inferred from the study, the information was recorded in the database (for above ground and soil carbon) as “Not reported”. In relation to climate information, the Met Office climate guide (Met Office, 2017) was used to reclassify the climate region reported by the studies into Arid, Mediterranean, Polar, Semiarid, Temperate and Tropical classes.

For soil carbon data, an extra step was required because this was usually reported for different soil depths, and often the upper and lower positions of the depth intervals did not match across studies. In order to allow a standardised analysis compatible with the IPCC guidelines, the quadratic density function (Eq. (1)) based on Smith et al. (2013) was used to derive a scaling cumulative distribution functions (c.d.f.) for soil density as a function of soil depth in (metres) up to 1 m as follows:

$$\mathbf{cdf\ (d)} = ((22.1 - (33.3d^2)/2 + (14.9d^3)/3))/10.4166 \qquad (1)$$

And Eq. (2) allowed soil carbon at a given depth (d) to be scaled to the equivalent values at 0.30 m as follows:

$$\mathbf{SOC\ (0.3\ m)} = \mathrm{SOC\ (d)} \times (\mathrm{cdf\ (0.3)})/(\mathrm{cdf\ (d)}) \qquad (2)$$