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Integrating belowground carbon dynamics into Yield-SAFE, a parameter sparse agroforestry model

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Abstract

Agroforestry combines perennial woody elements (e.g. trees) with an agricultural understory (e.g. wheat, pasture) which can also potentially be used by a livestock component. In recent decades, modern agroforestry systems have been proposed at European level as land use alternatives for conventional agricultural systems. The potential range of benefits that modern agroforestry systems can provide includes farm product diversification (food and timber), soil and biodiversity conservation and carbon sequestration, both in woody biomass and the soil.. Whilst typically these include benefits such as food and timber provision, potentially, there are benefits in the form of carbon sequestration, both in woody biomass and in the soil. Quantifying the effect of agroforestry systems on soil carbon is important because it is one means by which atmospheric carbon can be sequestered in order to reduce global warming. However, experimental systems that can combine the different alternative features of agroforestry systems are difficult to implement and long-term. For this reason, models are needed to explore these alternatives, in order to determine what benefits different combinations of trees and understory might provide in agroforestry systems.

This paper describes the integration of the widely used soil carbon model RothC, a model simulating soil organic carbon turnover, into Yield-SAFE, a parameter sparse model to estimate aboveground biomass in agroforestry systems. The improvement of the Yield-SAFE model focused on the estimation of input plant material into soil (i.e. leaf fall and root mortality) while maintaining the original aspiration for a simple conceptualization of agroforestry modeling, but allowing to feed inputs to a soil carbon module based on RothC. Validation simulations show that the combined model gives predictions consistent with observed data for both SOC dynamics and tree leaf fall. Two case study systems are examined: a cork oak system in South Portugal and a poplar system in the UK, in current and future climate.

Keywords: Ecosystem approach, RothC, climate change, soil, leaves, root, resilience

Introduction

In a context of sustainable agriculture intensification towards a circular bio-economy, and the need to mitigate the impact of atmospheric greenhouse gas emissions to reduce global warming, our knowledge of the carbon cycle plays a key role in supporting decisions on land use management. Agroforestry, while present in Europe on 15.4 million hectares of land covering almost 10% of the utilized agricultural area (den Herder et al. 2017), is also a promising option for designing new systems of sustainable agriculture. Interest in agroforestry is currently on the rise due to its potential to increase productivity, diversify farm landscapes, promote biodiversity, diversify farm products and income, whilst also providing functional benefits such as reducing wind damage, providing shade, enhancing soil, and reducing nitrogen leaching, flooding or erosion (Palma et al. 2007; Glover et al. 2012; Fagerholm et al. 2016).

Agroforestry systems also have implications for the global carbon cycle. They often have higher land equivalent ratios (Graves et al., 2007) therefore reducing the need for further agricultural land expansion and concomitant C losses from land use change. Furthermore these systems sequester carbon at higher rates than if the trees and crops are grown separately, they store carbon also in standing biomass or introduce carbon to the soil through, for example, leaf fall, root turnover or crop residues, reducing carbon in the atmosphere, which is essential for mitigating the effects of global warming (Schroeder 1994; Montagnini and Nair 2004; Upson 2014). Furthermore agroforestry systems may be more resilient to climate change than conventional agriculture because trees create microclimatic effects, potentially reducing extreme impacts (Gill and Abrol 1993; Shanker et al. 2005; Gosme et al. 2016; Martin-Chave et al. 2016).

As studying the possible combinations of trees and crops in field experiments can be highly limited, due to the length of time needed to assess indicators under different stages of tree growth, models can play a key role in understanding and assessing the dynamics of biophysical indicators (Ford 1999). However, there is a scarcity of modeling tools that can support land use decisions in an agroforestry context, whilst also including soil carbon dynamics and climate change scenarios.

Currently, carbon sequestration in agroforestry systems can’t be modeled precisely enough, especially the belowground component, hampering the account of this carbon sequestration in national greenhouse inventories. As agroforestry systems are not currently represented in common soil carbon models and humus-balancing methods we propose to close this gap by integrating the widely used soil carbon model RothC into Yield-SAFE, a parameter sparse model to estimate the aboveground biomass in agroforestry systems. Our aim is that the benefits of agroforestry on soil carbon sequestration can be quantified more precisely and integrated into national greenhouse gas inventories. Such integration is not only central to improving our knowledge on soil carbon dynamics under agroforestry systems but also allows comparison of carbon storage capacity between conventional treeless agriculture and agroforestry, considering future climate.

We assess the long-term dynamics of soil carbon in agroforestry systems using Yield-SAFE (van der Werf et al. 2007) while adding belowground state variables than can interact with our implementation of 'The Rothamsted Carbon Model' (RothC), (Coleman and Jenkinson 2014). The integration of both models is then used to compare arable and agroforestry alternatives under current and future climates.

Materials and Methods

Source models

Yield-SAFE is a parameter-sparse, process-based dynamic model for predicting resource capture, growth, and production in agroforestry systems (van der Werf et al. 2007). The model was developed with a simple architecture trying to capture the main processes of water and light use either for forest, conventional monocropping or the combination of both uses.

RothC, the "Rothamsted Carbon Model" (Coleman and Jenkinson 2014) is a model for the turnover of soil organic carbon developed by researchers at the UK agricultural research station focusing the model development into conventional agricultural practices.

Soil carbon additions through aboveground and belowground biomass

Trees can affect crop production in a number of ways, negatively through competition for light, nutrients and water, as well as positively through increased inputs of biomass to the soil from leaves and roots that often enhance nutrient cycling (Rao et al. 1998). Thus, although growth-impact nutrients (i.e. N, P, K) are not implemented in Yield-SAFE, the soil carbon dynamics module used in this paper (see Integrating RothC into Yield-SAFE) required some improvements to be made in Yield-SAFE so that the effect of the trees on soil carbon could be modeled.

Two main interactions were selected, the first, tree leaf fall and the second, fine root mortality from both trees and crops. All linked to existing state variables in Yield-SAFE and acted, in the new soil module, as plant carbon input material into soil.

The implementation of carbon added to soil from tree leaf fall was achieved in four steps. First, by defining the period of tree leaf fall, with a day of year for leaf fall start (DOY^{SLFall}) and the number of days leaves are falling ($NrDays^{LFall}$), and the proportion of leaf area that will fall (f^{LFall}). Second, by defining the biomass of leaves that will fall (B_{LFall}) on a particular day of the year DOY^{SLFall}, using the specific leaf area (*SLA*, cm^2 g^{-1}), a commonly available parameter in literature, which is multiplied by the existing state variable tree leaf area (LA_t, m^2 tree^{-1}) (Eq. 1). In the third step, the quantity of biomass falling from the tree was evenly distributed over all the leaf fall days, and was removed from the total biomass (Eq. 2). In the fourth step, a proportion of carbon content in the leaf biomass (f^{CCL}) usually around 0.5 (Thomas and Martin 2012), provided the amount of carbon added to the soil during tree leaf fall (Eq. 3).

$$B_{LFall} = \frac{LAt * 10000}{SLA} * f^{LFall} \; when \; DOY = DOY^{SLFall} \qquad \text{Eq. 1}$$

B_{LFall}, Total leaf biomass that will fall (g tree^{-1}); LAt, Tree leaf area (m^2 tree^{-1}); SLA, Specific Leaf Area (cm^2 g^{-1}); f^{LFall}, proportion of LAt that will fall (0-1); DOY, Day of Year; DOY^{SLFall}, DOY when leaves start falling

$$B_{LFall_k} = \begin{cases} \dfrac{B_{LFall} * \rho}{1000 * NrDays^{LFall}}, & DOY^{SLFall} \leq k \leq DOY^{SLFall} + NrDays^{LFall} \\ 0, & otherwise \end{cases} \qquad \text{Eq. 2}$$

(Note: Yield-SAFE tree biomass (g tree^{-1}) needs to be reduced by $\frac{B_{LFall}}{NrDays^{LFall}}$) when $B_{LFall_k} > 0$)

B_{LFall_k}, Leaf biomass fallen in day k (kg ha^{-1}); B_{LFall}, Total leaf biomass that will fall (g tree^{-1}); ρ, Tree density (trees ha^{-1}); DOY^{SLFall}, day of year when leaves start falling; $NrDays^{LFall}$, total number of days leaves are falling; B_{t_k}, tree biomass in day k (g tree^{-1})

$$\begin{gathered} C_{LF_k} = B_{LFall_k} * f^{CCL} \\ \text{when } DOY^{SLFall} < k < DOY^{SLFall} + NrDays^{LFall} \end{gathered} \qquad \text{Eq. 3}$$

C_{LF_k}, Carbon added to soil from leaf biomass in day k (kg ha^{-1}); B_{LFall_k}, Leaf biomass fall in day k (kg ha^{-1}); f^{CCL}, proportion of carbon content in leaf biomass (0-1); $NrDays^{LFall}$, total number of days leaves are falling, proportion of ; DOY^{SLFall}, day of year when leaves start falling

Fine root mortality is another source of carbon in soil. Root biomass in trees and crops can be estimated with a root-to-shoot ratio (*RSRt* and *RSRc, unitless*) where frequently used values for trees are 0.2 and 0.25 for conifers and broadleaf respectively (IPCC 2006) while for crops a wider range can be possible, e.g. 0.1 to 4.9 depending on nutrient, water availability, phenology and species (Bolinder et al. 1997; Gan et al. 2009; Munns et al. 2016). Once root biomass is estimated for trees and crops, separate estimates of carbon incorporation into soil need to be made.

Since literature suggests that tree fine roots can be a proportion of root biomass in the same proportion as leaves in aboveground biomass (e.g. Madeira et al., 2002) using the theory of a *whole-plant economics spectrum*, that considers a coupled behavior between leaf area and fine root biomass (Sloan et al. 2013), we suggest the estimation of tree fine root biomass as a proportion of whole root biomass based on the proportion of leaves to tree aboveground biomass (Eq. 4.1). Alternatively, in the model, a user can also define the proportion of fine roots in the belowground biomass (f^{FR}).

Thus, the root mortality rate, using the theory of the *whole-plant economics spectrum* (Eq. 4.1), then followed the same rate of change as for leaf fall (Eq. 5). Finally, using a proportion of carbon content in fine roots biomass (f^{CCFR}), about 10% less than the reference stem or leaf carbon contents (Thomas and Martin 2012), carbon added to soil in a particular day could be estimated (Eq. 6).

However, carbon from fine roots is not the only belowground source of carbon incorporated into soil. Larger quantities of carbon from roots are added when thinning or final harvesting of the trees occurs, and here we assumed that there would be no stump removal from the land since replanting of new trees would occur between the stumps (Eq. 7).

$$Bt_{FRoots} = B_t * RSR_t * \frac{B_{LFall}}{B_{0t}}, when\, DOY = DOY^{SLFall} \qquad \text{Eq. 4}$$

or, in its reduced form

$$Bt_{FRoots} = RSR_t * B_{LFall}, when\ DOY = DOY^{SLFall}$$ Eq. 4.1

Bt_{FRoots}, Biomass of tree fine roots that will die (g tree^{-1}); B_t Aboveground tree biomass (g tree^{-1}), RSR_t, Tree root-to-shoot ratio (0-1); B_{LFall}, Total leaf biomass that will fall (g tree^{-1}); DOY, Day of Year; DOY^{SLFall}, DOY when leaves start falling

$$Bt_{FRoots_k} = \\ = \begin{cases} \dfrac{Bt_{FRoots} * \rho}{1000 * NrDays^{LFall}}, & DOY^{SLFall} \leq k \leq DOY^{SLFall} + NrDays^{LFall} \\ 0, & otherwise \end{cases}$$ Eq. 5

Bt_{FRoots_k}, Fine roots biomass died in day *k* (kg ha^{-1}); Bt_{FRoots}, Biomass of tree fine roots that will die (g tree^{-1}); ρ, Tree density (trees ha^{-1}); DOY^{SLFall}, day of year when leaves start falling; $NrDays^{LFall}$, total number of days leaves are falling

$$C_{FR_k} = Bt_{FRoots_k} * f^{CCFR}$$ Eq. 6

$$\text{when } DOY^{SLFall} < k < DOY^{SLFall} + NrDays^{LFall}$$

C_{FR_k}, Carbon added to soil from fine roots in day k (kg ha^{-1}); Bt_{FRoots_k}, Fine roots biomass died in day *k* (kg ha^{-1}); f^{CCFR}, proportion of carbon content in fine root biomass (0-1); DOY^{SLFall}, day of year when leaves start falling

$$C_{CR_k} = Bt_k * RSR_t * f^{CCCR} * N_{harv}$$ Eq. 7

$$\text{when } k = DOY^{Harvest}$$

C_{CR_k}, Carbon added to soil from coarse roots in day k (kg ha^{-1});); B_t Aboveground tree biomass (g tree^{-1}), RSR_t, Tree root-to-shoot ratio (0-1); f^{CCCR}, proportion of carbon content in coarse roots biomass (0-1); N_{harv}, number of trees harvested (trees ha^{-1}); DOY^{Harves}, day of year when thinning (or harvesting) occurs

Crop root biomass is estimated with a root-to-shoot ratio (Eq. 8) while carbon added into soil is estimated with simpler dynamics as the root biomass and corresponding carbon is added to soil when the crop is harvested (Eq. 9). Furthermore, additional carbon addition into soil can also be considered because the harvesting process might not collect all aboveground biomass (Eq. 9).

$$Bc_{Roots_k} = B_{c_k} * 10 * RSR_c$$ Eq. 8

Bc_{Roots_k}, Biomass of crop roots in day *k* (kg ha^{-1}); B_{c_k} Aboveground crop biomass in day *k* (g m^{-2}), RSR_c, crop root-to-shoot ratio (0-1); (10 is the conversion factor from g m^{-2} to kg ha^{-1})

$$C_{Croots_k} = Bc_{Roots_k} * f^{CCCR} + 10 * Bc_k * (1 - HI_{crop} - HI_{byproduct})$$ Eq. 9

$$when\ k\ is\ day\ of\ crop\ harvest$$

C_{Croots_k}, Carbon added to soil in day *k* from crop roots (kg ha^{-1}); Bc_{Roots_k} , Biomass of crop roots in day *k* (kg ha^{-1}), f^{CCCR} proportion of carbon content in crop root biomass (0-1); Bc_k crop biomass (g m^{-2}); HI_{crop}, crop harvest index (0-1); $HI_{byproduct}$, by product (e.g. straw) harvest index (0-1); (10 is a conversion factor from g m^{-2} to kg ha^{-1})

Integrating RothC into Yield-SAFE

The original RothC model uses a monthly time step to calculate total organic carbon (Mg ha^{-1}), microbial biomass (Mg ha^{-1}) and Δ^{14}C (which allows the calculation of the radiocarbon age of the soil) on a years to centuries timescale.

In brief, the model takes incoming organic matter inputs, and splits these into one inert (IOM) and four active soil organic matter pools. Active organic matter is split between two pools: 1) Decomposable Plant Material (DPM), and 2) Resistant Plant Material (RPM), using a ratio dependent on the type of plant material[1]. These two fractions are further split into three products of decomposition: CO2, microbial biomass (BIO), and Humified Organic Matter (HUM). The proportion of SOC that is lost as CO_2 is determined by soil clay content (as this affects the ability of organic matter to be immobilized in organo-mineral complexes). Both the BIO and HUM fraction are split again into subsequent CO_2, BIO, and HUM pools. A proportion of 46% for BIO and 54% for HUM for the BIO+HUM compartment is considered. Farmyard manure applied as input material is considered to contain 49% DPM, 49% RPM and 2% HUM.

The link between the models was made with climate, crop, tree and water state variables in Yield-SAFE being used as inputs to RothC, including the new estimations for tree leaf fall biomass and trees and crop root mortality (see previous section). The model can also include the application of manure from livestock as carbon inputs to the soil. However, it should be noted that none of these outputs provide feedback to modify crop or tree yields within the Yield-SAFE model. Please refer to the Electronic Supplementary Material #1 for detailed list of equations used.

RothC is a monthly time step model and therefore some adaptations were made to fit it to the daily time-step used in Yield-SAFE, in particular the decomposition rate constants that needed to be converted into daily rates (see Electronic Supplementary Material #2 for details on parameters units and values used).

As long term data on soil carbon measurements is scarce (Schroth and Zech 1995), the model integration was validated with the same observed data as those reported by Coleman and Jenkinson (2014). The model was set up to represent the same conditions as those reported by the authors: Ccsoil=0.234, $\text{Soil}_{\text{DepthOM}}$=23 cm, DPM_RPM_r=1.44 and an initial SOC=33.86 Mg ha^{-1}, with a continuous crop rotation of spring barley (*Hordeum vulgare* L.) (see Electronic Supplementary Material #1 for parameters description). The same weather data as Coleman and Jenkinson (2014) was used, where monthly temperature was set as the daily temperature for each month, and monthly precipitation was divided by 30 for each day of each month.

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[1] DPM/RPM ratios are proposed in Coleman and Jenkinson (2014) for Agricultural crops and improved grasslands (1.44; 59% DPM and 41% is RPM), Unimproved grasslands and scrub (0.67; 40% DPM and 60% RPM); Deciduous or tropical woodland (0.25; 20% DPM and 80% RPM) and Farmyard manure (1; DPM 49%, RPM 49% and HUM 2%). When day of tree harvest occurs, the ratio between DMP and RPM is considered 0.25

A calibration was done for barley (see Graves et al 2007 for calibration procedure details) and, for validation purposes, three scenarios were used: 1) unmanured, 2) manured and 3) partially manured. Table 1 summarises the carbon added to soil through the addition of manure over the 148 years of experimentation. As manure is not yet included in Yield-SAFE, the carbon content from this source was added manually in the model.

Table 1. Carbon added to soil in manured and partially manured validation scenario (adapted from Coleman and Jenkinson (2014)

Years	Scenario	
	Manured (Mg C ha^{-1})	Partially Manured (Mg C ha^{-1})
1852-1871	3	3
1872-1911	3	0
1912	0	0
1913-1930	3	0
1931	3 + 3	0
1932-2000	3	0
1933, 1943, 1967	0	0

Note: Until 1930, manure was applied in DOY=45 (15 Feb). In 1931 an additional application was made on DOY=318 (15 Nov). The applications from 1932 onwards were done in DOY=318 (15 Nov). In the no-manured scenario in years 1912, 1933, 1943 and 1967, land was set to fallow (no input plant material)

Agroforestry simulation scenarios

After the Yield-SAFE and RothC models were integrated, a comparison between conventional arable and agroforestry land use alternative was made for two different locations and different growth rate tree species for a simulation horizon of 80 years. The first was in a Mediterranean climate, and compared an arable system with a wheat-wheat-fallow rotation to an agroforestry system with the same rotation and a density of 78 trees ha^{-1} (holm oak – *Quercus rotundifolia* L.) over an 80 year time horizon. The second was in an Atlantic climate, and compared an arable system with a wheat-wheat-barley-oilseed rotation to an agroforestry system with the same rotation and a density of 78 trees ha^{-1} (poplar – *Populus* sp) over a 20 year time horizon. For details on Yield-SAFE calibration for these species, see Oliveira et al (this special issue) and Crous-Duran et al (this special issue).

The daily climate input for the simulations was obtained through CliPick (Palma 2017) for locations near Montemor (South Portugal) and Silsoe (Central UK), either for current or future climate (scenario RCP8.5), the latter used for assessing impacts of climate change.

Results and discussion

The integration of RothC into Yield-SAFE was very challenging as RothC is in itself a large and complex model. The only long term data to validate the implementation were those used in the RothC model itself. Nevertheless, they are still valid as independent data, but as they were obtained in pure agricultural conditions, they can be used to validate only the new RothC implementation and crop residues input, not the tree litter carbon input.

The simulations of the Rothamsted experiment show an interesting resemblance to the validation reported by Coleman and Jenkinson (2014) indicating that the conceptual integration, formulation of state variables and decomposition rates for time scale adaptation presented in this manuscript are replicating RothC dynamics whilst also including the crop carbon inputs driven by Yield-SAFE (Figure 1).

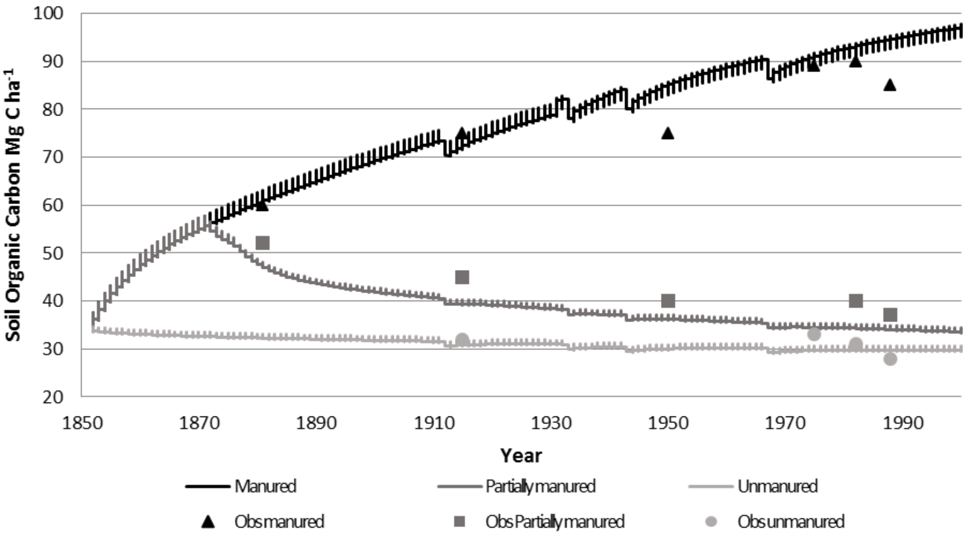

Figure 1. Daily simulation of the Rothamsted experiment using Yield-SAFE integrated with RothC for three manure management scenarios. Obs, Observed data adapted from Coleman and Jenkinson (2014)

For the validation of tree leaf and root litter inputs, two simulations were performed with the modified Yield-SAFE model. for: 1) a perennial cork oak plantation of 575 trees ha^{-1} in South Portugal (near Montemor) and 2) a deciduous poplar plantation of 156 trees ha^{-1} in United Kingdom (near Bedfordshire) - Figure 2. The simulations show results that are in accordance with literature. For example, Caritat et al. (1996) reported annual leaf litter falls of between 3.5 and 4.5 Mg for stands of cork oak at a density of 575 trees ha^{-1} while poplars in Poland were found to yield about 1.4 Mg ha^{-1} of leaves in year 17 at a density of 88-118 trees ha^{-1} based on a reported leaf litter estimate of 9 kg tree^{-1} year^{-1} (Dziadowiec et al. 2008).

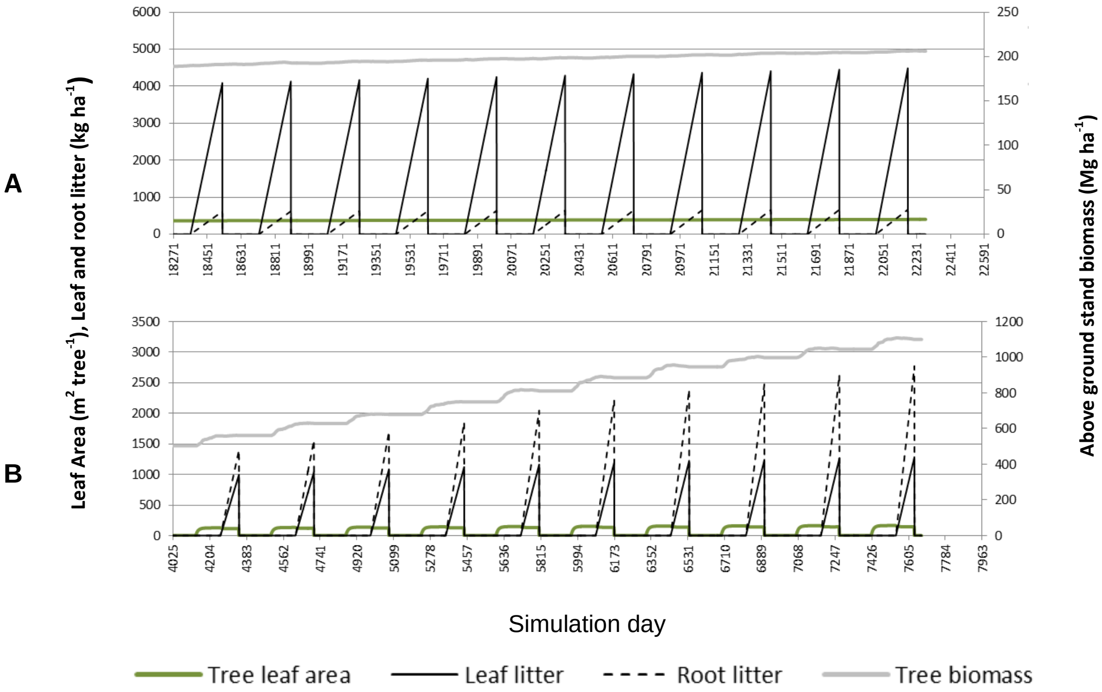

Figure 2. Leaf area, leaf fall and rootSimulation of A) a perennial stand (*Quercus suber* L.) in South Portugal (near Montemor), showing years 50-60 with 575 trees ha^{-1} and B) a deciduous stand (*Populus sp.*) with 156 trees ha^{-1} in the United Kingdom (in Bedfordshire) showing years 10-20.

For fine root biomass, there is little literature available to validate the model. However, it has been observed that the fine roots biomass follows the theory of a whole-plant economics spectrum, and that this can therefore be used to couple the behavior of fine root mortality to leaf litter production (Sloan et al. 2013). The difference between the perennial and deciduous trees suggests that the algorithms in Yield-SAFE are adequate to reflect the differences in leaf litter production as the perennial trees, although having greater standing biomass and root biomass, provide less root-origin biomass in soil because only a small fraction of the total leaf biomass is dropped as leaf litter, and therefore only a fraction of the fine root biomass is released into the soil (Figure 2).

To explore the advantages of the integration of both models to assess the effect of introducing trees in farmland, a comparison between arable and agroforestry land use scenarios was made in Mediterranean and Atlantic environments using a slow growing perennial tree species and a fast growing deciduous tree species.

The simulations predicted that in both environments, agroforestry would increase soil organic content when compared to conventional arable agriculture. Although this is somewhat expected through previous studies (Schroeder, 1994; Montagnini and Nair, 2004), the ability to assess soil carbon dynamics and quantify carbon storage in the long-term through dedicated agroforestry models is an improvement to the set of tools that are available for assessing agroforestry land use changes. In the Mediterranean scenario, the effect of the cork oak trees was to increase SOC by about 1 Mg ha^{-1}, but when compared to conventional agriculture, after 80 years, there was a difference of 2.5 Mg ha^{-1} because agricultural land use tends to decrease the carbon content of the soil (Figure 3A), with or without conservation measures (Hermle et al. 2008; SOILSERVICE 2012; Oberholzer et al. 2014). Similar results for similar systems are reported by Francaviglia et al. (2012) in Sardinia where input plant materials for a cork oak forest were of 3.74 Mg ha^{-1} (and considering 0.5 Mg ha^{-1} of manure from livestock) giving an increase of 10% of SOC in about 90 years. However, simulations seem conservative when compared to results obtained by Cardinael et al. (2017) that found carbon being accumulated in about 0.24 Mg C ha^{-1} y^{-1} (9.6 Mg C ha^{-1} for 40 years).

In the Atlantic scenario, during the 80-year simulation horizon, there was additional carbon added by coarse roots of the poplar when each 20-year tree rotation ended. These fluctuations in soil carbon increased the mean carbon content of the soil over the 80-year simulation time horizon. However, even when not considering the carbon peaks created by the coarse roots input, the results still showed a difference, after 80 years, of about 10 Mg ha^{-1} between the arable and agroforestry systems.

Under future climate change, the simulations suggested that, in Mediterranean areas, soil carbon storage was more resilient under agroforestry systems. The model suggested a reduction in carbon storage of about 2 Mg ha^{-1} and 5 Mg ha^{-1} in the agroforestry and arable systems, respectively (Figure 3A). The reduction of yields where rain fed yields are already low, was mainly due to increased water scarcity, a projected characteristic of future climate for Mediterranean areas, which will need adaptive management (Christensen et al. 2007; Palma et al. 2015). In the Atlantic environment, climate change, although having a negative impact, was not as dramatic as in the Mediterranean case (Figure 3A). Furthermore, the agroforestry scenario still increased carbon in the soil showing, as in the Mediterranean case, that in terms of soil carbon storage, agroforestry land use was more resilient to climate change than arable land use.

It is worth noting that there are additional factors affecting carbon dynamics that might play an important role in agroforestry systems (Lorenz and Lal 2014) that the model is not considering. For example improvements can be made to the partitioning of the decomposition rates, as it is known that root litter usually decomposes more slowly than leaf litter of the same tree species (Cusack et al. 2009). In addition, higher carbon accumulation rates found by Cardinael et al. (2017) suggest that improvements in the model regarding the partitioning the decomposition dynamics of the DPM and RPM should be prioritized. The higher accumulation rates may be achieved with the increase of RPM proportion through time due to tree litter (leaves, branches, roots) in comparison to DPM (mostly from crop), leading to a slower decomposition with consequent higher carbon retention in soil. Also, soil erosion is lower under agroforestry systems and this could also reduce loss of carbon (Lal 2005; Palma et al. 2007). Furthermore, in alley cropping systems, the grass strip around the tree line seems to be of high relevance for carbon storage, especially in earlier stages of the agroforestry systems' establishment (Cardinael et al. 2017). Such additional factors mean that our simulated carbon storage under agroforestry might be underestimated.

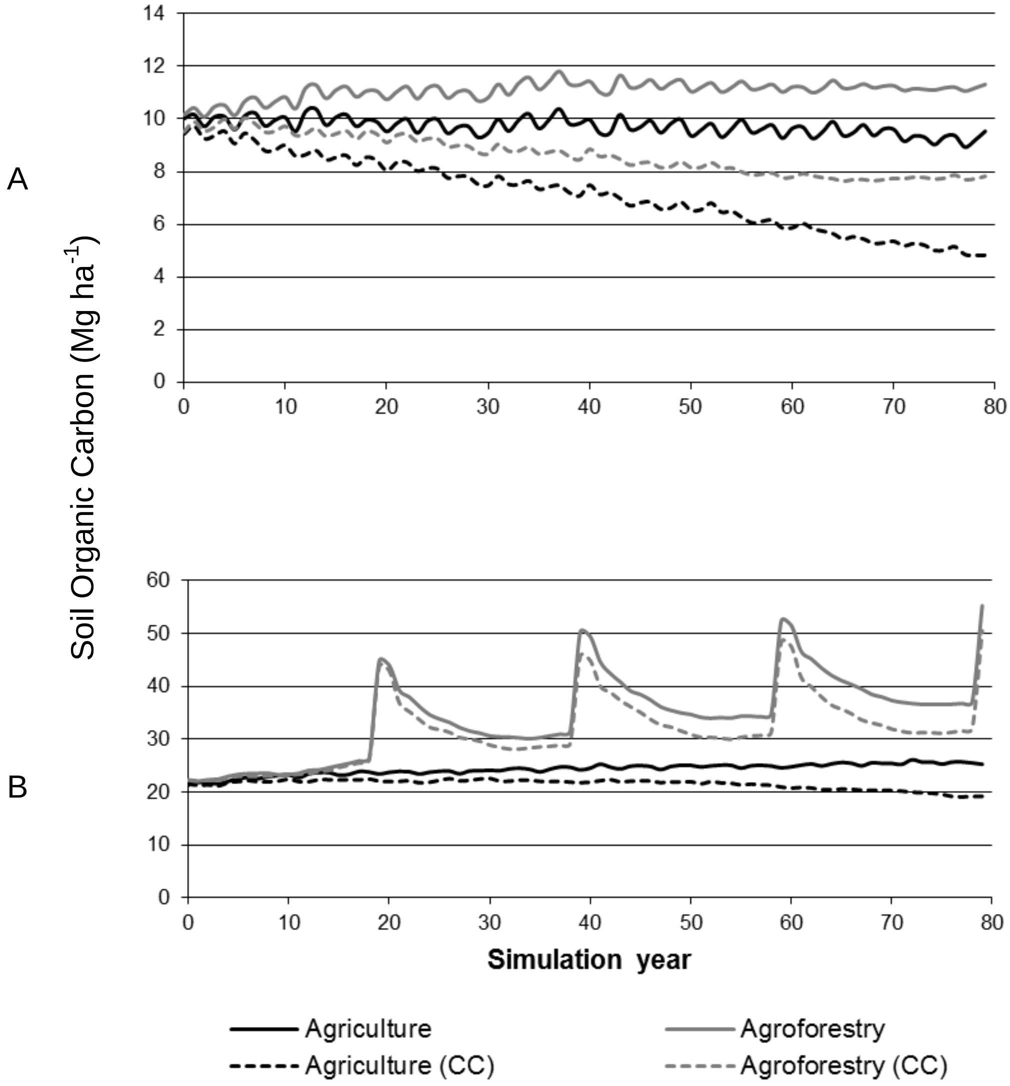

Figure 3. Comparison of simulated soil organic carbon between agroforestry and conventional agriculture in mediterranean (A) and atlantic (B) environments, using the integration of RothC and Yield-SAFE without and with climate change (CC). Both agroforestry systems are simulated with 78 trees ha^{-1}. Mediterranean case has a rotation of wheat-wheat-fallow and the agroforestry system has a perennial tree (*Quercus rotundifolia* L.). Atlantic case has a rotation of wheat-wheat-barley-oilseed and the agroforestry system has a deciduous tree (*Populus* sp) harvested each 20 years. Future climate is the Representative Concentration Pathway 8.5 simulated by the KNMI RACMO climate model (see Palma 2017 for details).

Although this paper is an initial step towards the development of a carbon assessment tool in agroforestry systems with margin to progress, this work is part of a set of further improvements currently undergoing, in particular merging algorithms for assessing silvopastoral systems and widening the calibration for more tree and crop species across Europe and more validation data is needed to confirm the simulated soil carbon dynamics.

Conclusions

The integration of a carbon dynamics module (RothC) into Yield-SAFE has improved our ability to assess long-term soil carbon storage under different land uses, including agroforestry land uses. Using a simple modelling philosophy, i.e. keeping a parameter sparse concept, Yield-SAFE can now also be used to assess how land use change impacts on an important ecosystem service, carbon storage in soil, which could have an important role to play in mitigation of climate change impacts.

A climate change assessment of different land uses under different climatic regions demonstrated how the model could be used. The assessment indicated that agroforestry is a more resilient land use system under future climate change, and will retain and input higher levels of carbon in the soil in comparison with conventional arable agriculture. The trends in our simulated results are consistent with existing data and theory but now, integration of RothC and Yield-SAFE, can allow quantitative predictions to be made to assess how land use systems, including agroforestry systems, will impact carbon storage levels in the long-term.

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