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Changes in soil organic carbon under perennial crops

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Abstract

This study evaluates the dynamics of soil organic carbon (SOC) under perennial crops across the globe. It quantifies the effect of change from annual to perennial crops and the subsequent temporal changes in SOC stocks during the perennial crop cycle. It also presents an empirical model to estimate changes in the SOC content under crops as a function of time, land use, and site characteristics. We used a harmonized global dataset containing paired-comparison empirical values of SOC and different types of perennial crops (perennial grasses, palms, and woody plants) with different end uses: bioenergy, food, other bio-products, and short rotation coppice. Salient outcomes include: a 20-year period encompassing a change from annual to perennial crops led to an average 20% increase in SOC at 0–30 cm (6.0 ± 4.6 Mg/ha gain) and a total 10% increase over the 0–100 cm soil profile (5.7 ± 10.9 Mg/ha). A change from natural pasture to perennial crop decreased SOC stocks by 1% over 0–30 cm (−2.5 ± 4.2 Mg/ha) and 10% over 0–100 cm (−13.6 ± 8.9 Mg/ha). The effect of a land use change from forest to perennial crops did not show significant impacts, probably due to the limited number of plots; but the data indicated that while a 2% increase in SOC was observed at 0–30 cm (16.81 ± 55.1 Mg/ha), a decrease in 24% was observed at 30–100 cm (−40.1 ± 16.8 Mg/ha). Perennial crops generally accumulate SOC through time, especially woody crops; and temperature was the main driver explaining differences in SOC dynamics, followed by crop age, soil bulk density, clay content, and depth. We present empirical evidence showing that the FAO *perennialization* strategy is reasonable, underscoring the role of perennial crops as a useful component of climate change mitigation strategies.

KEYWORDS

agriculture, arable crops, carbon balance, emission factors, fruit crops, land use change, meta-analysis, woody crops

1 | INTRODUCTION

Soils store approximately 1,550 Gt of organic carbon out of the 2,110 Gt of organic carbon estimated to be present in the biosphere (Lal, 2004). Thus, soil organic carbon (SOC) accounts for about 70% of total terrestrial carbon (C), and represents more than twice the 760 Gt of atmospheric C (IPCC, 2014). The size of the SOC pool means that land use and land use changes (LUCs) that cause soil disturbance can lead to substantial loss of SOC and greenhouse gas (GHG) emissions. Indeed, conversion from natural to agricultural ecosystems causes a major loss of SOC: up to 60% or 75% in temperate and tropical regions, respectively (Lal, 2004), and this C is released to the atmosphere as carbon dioxide, CO_2, a GHG source. Agriculture is practiced on 49% of the global ice-free land surface, 12% as cropland, and 37% as pasture, and is responsible for 12% of the total direct anthropogenic GHG emissions (IPCC, 2019). If, in addition, LUC and degradation are considered, the contribution of agriculture rises to one third of the total anthropogenic emissions (Wollenberg, Tapio-Bistrom, Grieg-Gran, & Nihart, 2011). Furthermore, the reduction in SOC causes soil degradation and hence reduces plant productivity and yield (Lal, 2006). Agriculture, however, is a basic human activity and a necessity, and as such, providing secure food and energy supply for rising global population while minimizing GHG emissions is one of the main challenges of humanity (Smith et al., 2010). The agriculture, land use, and forestry sectors are the only major sectors with the potential not only to reduce emissions but also deliver negative emissions in some cases (Ledo, Heathcote, Hastings, Smith, & Hillier, 2018). This is achieved via C sequestration (Smith, 2004) and/or offsetting through the supply of feedstock for energy production (Robertson et al., 2017).

It is estimated that agricultural lands have the potential to sequester up to a 66% of historical C loss, if managed properly (Lal, 2004). The "4 per mille" initiative (https://www.4p1000.org/), which aims to increase SOC relies mainly on the application of best agricultural practices and the reduction of deforestation. Tree planting is an effective method increasing SOC (Laganiere, Angers, & Pare, 2010). Another method for increasing SOC is the establishment of perennial crops, which may be applied without loss of productive area. This latter option might deliver food, fiber, energy feedstock, or other goods and ecosystem services including increasing SOC, and as such could represent a win–win scenario. In fact, the FAO has suggested "perennialization" of agricultural lands as a strategy to mitigate climate change, and to enhance food security and ecosystem service delivery (Glover, Reganold, et al., 2010). Nonetheless, to date there has been a lack of evidence about the capacity of perennial crops to store SOC (Ledo et al., 2019). Importantly, studies have been carried out in a range of locations, using different experimental designs and analytical methods, and for a wide variety of crops. Therefore, results are not directly comparable and conclusions on the effect of perennial crops on SOC and soil properties cannot easily be derived. This is a significant limitation and knowledge gap considering that, even currently, perennial crops comprise 30% of global croplands (Ledo et al., 2018). There is thus a clear need to collate and carry out standardized analysis and syntheses of results from these disparate studies in order to understand the global impacts of LUCs and conversions under such significant production systems and/or scale; as well as to identify critical information or data gaps.

Perennial crops in this study are defined as crops that are planted, but not replanted and/or fully harvested annually to obtain goods (this definition excludes naturally occurring perennials and grasslands but includes plants for which the above-ground biomass is annually harvested). Perennial crops can be divided in two main groups: woody plants, such as fruits and nut crops (e.g., apple trees, citrus, almond), beverage crops (e.g., coffee, tea, cocoa), oil crops (e.g., palms), or short rotation coppices (e.g., poplar, willow); and perennial grasses such as sugarcane, switchgrass, *Miscanthus*. They also have different end uses, such as food (e.g., fruits), fiber (e.g., cotton), bioenergy (e.g., *Eucalyptus*, *Miscanthus*). In perennial crop cultivation, tillage and soil disturbances are reduced since, by definition, perennial crops stay on the land for more than 1 year. Moreover, perennial crops ensure vegetation cover and thus photosynthesis all year around which increases the biomass that is produced and left on the site to become SOC. Thus, there is greater potential to maintain or sequester SOC relative to annual crops. Along with potential benefits for soils (Cox, Glover, Tassel, Cox, & DeHaan, 2006; Paustian, Six, Elliott, &

Hunt, 2000) and GHG emission reduction, perennial crops store biomass (Ledo et al., 2018) and/or may be used to displace fossil fuels for energy generation (Dondini, Hastings, Saiz, Jones, & Smith, 2009; Robertson et al., 2017).

LUC and competition for land are urgent challenges for humanity (Foley et al., 2005; Smith et al., 2010). Given current rates of global population growth, the ongoing change from natural to cultivated ecosystems is likely to continue in order to feed an increasing population. It has been documented that a change from a natural ecosystem, forest or grassland, to annual cropland will result in SOC loss (Deng, Zhu, Tang, & Shangguan, 2016; Don, Schumacher, & Freibauer, 2011; IPCC, 2014). However, changes from natural ecosystems to perennial crops have been documented only locally and results are not consistent, reporting SOC gain (Post & Kwon, 2000; Robertson et al., 2017), SOC loss (Crowther et al., 2016; Don et al., 2011) or no change (Fialho & Zinn, 2014; Qin, Dunn, Kwon, Mueller, & Wander, 2016). Moreover, little information is available about the effects on SOC following conversion from annual to perennial crops. Furthermore, the SOC stock changes during the subsequent cultivation of perennial crops are poorly quantified. Turnover of soil organic matter is a function of several interacting variables, such as moisture, temperature, clay content, soil porosity, soil cover, and the composition of the soil microbiota (Aguilera, Lassaletta, Gattinger, & Gimeno, 2013; Blagodatsky & Smith, 2011; Deng et al., 2016; Don, Böhme, Dohrmann, Poeplau, & Tebbe, 2017). However, the most important driver for SOC turnover and changes is the C input via root litter and exudates, above-ground litter, and organic amendments (Kutsch, Bahn, & Heinemeyer, 2009; Rasse, Rumpel, & Dignac, 2005). Differences among crops and geographic areas may be largely explained by differences in these variables. Furthermore, an increase in global temperatures may affect SOC dynamics and C input to the soil (Davidson & Janssens, 2006).

In this study, we have used the first global and harmonized dataset of perennial crops on SOC dynamics (Ledo et al., 2019) to explore, at a global level, SOC in perennial crops. We studied different aspects: First, the changes in SOC stocks after a transition to perennials over a 20-year period or more, from different land uses: annual crops, forest (both natural and secondary forest) and natural grasslands. Secondly, we also evaluated changes in SOC stocks during the lifespan of the perennial crops, between 1 and 20 years after transition. Finally, we explored SOC changes in different biogeographical regions and for different perennial crops in order to identify general or distinctive patterns of SOC dynamics. Our final goal was to provide an empirical model to predict changes in SOC as a function of the main drivers of SOC dynamics found in this study: crop, climate, soil properties, and land use.

2 | METHODS

2.1 | Database creation

We used a global dataset of paired observations containing information about changes in SOC under perennial crops (Ledo et al., 2019), freely downloadable from the figshare file, https://doi.org/10.6084/m9.figshare.7637210 (2019). In addition to the original dataset, we calculated extra fields which were required in this study. This updated dataset is reproduced in Table S1. Firstly, for those plots without bulk density (BD) or soil texture (sand, silt, clay) and/or pH values in the original studies, we gap-filled the missing values as described previously (Ledo et al., 2019). Secondly, in order to standardize the units of SOC we transformed all values of SOC given as C density (SOC_{den}; g/kg) to SOC stocks (SOC_{stock}; Mg/ha) as follows:

$$SOC_{stock} = SOC_{den} * BD * depth \tag{1}$$

where BD is the bulk density (g/cm^3) and depth (cm) was the maximum depth at each particular measured plot.

This transformation may introduce errors and/or bias (Poeplau, Vos, & Don, 2017) but was deemed necessary due to lack of equivalence in reporting. Thirdly, for those plots with values of SOC at different depths, we calculated a single, depth-integrated value per sampling point by adding the SOC values of each layer. Consequently, we created a second database containing a single value of SOC stock per measured plot, whereas the original dataset has points with values of SOC at different depths (from 1 to 200 cm). This second dataset is reproduced in Table S2.

Finally, we calculated the relative change in SOC (ΔSOC_{rel}) for each point i between two times, t_0 (first measurement in time) and t_1 (second measurement in time, more recent, of the paired data information) as:

$$\Delta SOC_{rel_i} = \frac{SOC_{i,t_1} - SOC_{i,t_0}}{SOC_{i,t_0}} \tag{2}$$

We used the values of SOC as provided in the original study, either as SOC stocks (Mg/ha) or as SOC density (g/kg), to minimize errors and bias. SOC_{t_1} is the recorded empirical value of SOC after LUC to perennial crop cultivation; and SOC_{t_0} is the SOC value either (a) on previous land use before conversion to a perennial crop for those plots containing paired observations on two land uses, or (b) the earlier of observations at two different time points for those plots containing paired information on temporal changes on SOC during perennial cultivation. Positive values therefore indicate an SOC gain and negative values SOC loss.

We additionally calculated the stock change for every point i between times t_0 and t_1 in Mg/ha as:

$$\Delta SOC_{stock_i} = SOC_{i,t_1} - SOC_{i,t_0} \tag{3}$$

A summary of the SOC stock values recorded in the dataset evaluated in different biogeographical regions and main crop groups can be found in Appendix S1. The biogeographical regions considered were temperate, tropical, and boreal. The crop types were perennial grasses, woody plants, and palms (Ledo et al., 2019).

2.2 | Effect of LUC to a perennial crop on SOC in a 20-year period

We evaluated the change in SOC stock (ΔSOC_{stock}, Equation 3) from forest, grassland, or annual crops to perennial crops, using paired data. To align with the IPCC standards and provide relative stock changes over a 20-year period, we selected and included in our analysis only those studies where conversion to a perennial crop occurred more than 20 years ago (n = 138 plots). For such observations, we calculated the mean and the standard error of the mean (*SEM*) of the SOC values before and after conversion (ΔSOC_{stock}) and the percentage of SOC stock change. Furthermore, to avoid introducing additional errors and/or bias, rather than unifying values of SOC at a particular depth, we selected those plots containing information on SOC at depths (a) 0–30 cm (n = 105) and (b) 0–100 cm (n = 33).

2.3 | Temporal change in SOC under perennial plantations during the first 20 years after conversion

We evaluated changes on SOC stocks (ΔSOC_{stock}, Equation 3) over a 20-year period, from crop age 1 year to crop age 20 years. We selected a 20-year period as in the previous subsection and for the same reasons. We also included in our analysis those plots with SOC measured at 0–30 cm (n = 111) and 0–100 cm (n = 10) aggregated over different perennial crop types. Additionally, we calculated temporal ΔSOC_{stock} for perennial grasses, woody plants, and palms separately.

2.4 | Model to estimate temporal changes in SOC under perennial crops

We fitted a model to explain and predict the changes in SOC stocks and to identify the most significant explanatory variables and rank their importance. The explanatory variables we considered were (a) climatic: mean annual temperature, annual accumulated precipitation, climatic water deficit defined in Chave et al. (2015), and the variables Bio17 (Isotherma), Bio16 (changes in seasonal temperature), and climatic PT10 parameter, Bio12/(Bio 1 + 10), from the WorldClim database; (b) topographic: elevation, slope, aspect, and roughness (concavity or convexity of the terrain); (c) soil parameters: BD, percent clay, percent silt, percent sand, and pH; and (d) plantation parameters: crops age, years since transition to perennials, previous land use (annual crop, fallow, grassland, or natural forest), and current land use (agroforestry, bioenergy grass, or food and bio-products). More details on these variables can be found in Ledo et al. (2019). The response variable of this model was the rate of change in SOC, ΔSOC_{rel}, and we chose to fit a parametric model to make further predictions feasible. Since the variable ΔSOC_{rel} contained both positive and negative values and was highly skewed, we added 2 to all values and log-transformed the resultant data. After this transformation all the values of the response variable were positive, and the distribution was approximately normal. We then modelled the transformed ΔSOC_{rel} with a generalized lineal mixed model (GLMM), with a Gaussian distribution as identity link function.

To this end, we formulated several GLMMs, including systematically different sets of covariates and combinations, using both a Gaussian and Gamma distribution as identity link functions. Continuous explanatory variables were mainly but not exclusively tested and included as fixed effects and categorical variables were tested mainly, but not exclusively, as random effects. We used a Bayesian inference framework, an approach that allowed us to get information of the dispersion of the fitted parameters. We used the INLA (integrated nested Laplace approximation) method (Rue, Martino, & Chopin, 2009). The INLA method is a computationally efficient method for fitting Bayesian models that speeds up parameter estimation substantially in comparison with the typical Markov chain Monte Carlo routine. To identify the best model, we selected the model with lower log-likelihood among those containing all the covariates that were significant and not highly correlated and which residuals diagnose was acceptable. Including different sets of covariates and checking those that were significant was a manual, stepwise process.

Secondly, we calculated the variance in the data, and the variance explained by the model and by each of the explanatory covariates. In this way, we were able to rank the effect of each variable over the others and assess the importance of all of them in explaining and potentially predicting changes in SOC.

The R code used for all the analyses in this study can be found in Data S1 Programming Code 1.

3 | RESULTS

3.1 | Effect of LUC to perennial crop on SOC in a 20-year period

Overall, a change from an annual to a perennial crop led to a 20% (±10) increase in the SOC average stock values over a 20-year period in the top 30 cm and an increase of 11% (±8) over 100 cm (Table 1). In contrast, SOC stocks decreased when changing from grassland to perennial cops. We observed an averaged 0.6% (±5.65, not significant) SOC stock loss when only the first 30 cm were considered and a −9.6% (±6.7) when 100 cm were analyzed (Table 1). While the C loss in the upper layers was not significant, the effect of SOC loss was more obvious when the entire soil profile was considered. For a change from forest to perennial crops, we observed a 2% (±6.9, not significant) increase in SOC stocks in the upper part of the soil, but a 24% (±9.3) decrease when the entire profile was considered (Table 1). However, only seven paired plots contained information on this kind of LUC and natural and secondary forest were merged.

TABLE 1 Mean values of SOC (soil organic carbon) stocks (Mg/ha) and standard error of the mean before and after conversion to perennial with land use change more than 20 years ago. Significant effects are in bold

Previous land use	SOC before conversion (Mg/ha)	SOC after conversion (Mg/ha)	ΔSOC_{stock} (Mg/ha)	Gain/loss	% change
Depth 0–30 cm					
Annual crop	41.1 (±5.0)	47.1 (±6.3)	6.1 (±4.6)	**Gain**	**20 (±10.0)**
Grassland	58.7 (±7.4)	55.0 (±6.4)	−2.5 (±4.1)	Loss	−0.6 (±5.6)
Forest	84.5 (±40.8)	100.6 (±12.3)	16.8 (±55.1)	Gain	2.0 (±6.9)
Depth 0–100 cm					
Annual crop	139.0 (±44.9)	144.7 (±42.9)	5.7 (±11.0)	**Gain**	**11 (±8.5)**
Grassland	121.9 (±12.5)	108.3 (±11.8)	−13.6 (±8.9)	**Loss**	**−9.6 (±6.7)**
Forest	173.5 (±22.5)	133.4 (±28.2)	−40.1 (±16.8)	**Loss**	**−24 (±9.3)**

3.2 | Temporal change in SOC stocks during perennial plantation

Overall, an increase in SOC stocks over time after conversion to perennial crops in the upper soil layers was observed (Figure 1a), meaning a gain in SOC through the first 20 years after conversion to perennial crops. This trend was consistent for all crop types, although woody plants tended to accumulate progressively more SOC than grasses and palms (Figure 1b). However, the time lags in which the database contains information also differed between crop types, which was a confounding factor. Upon close observation, it was apparent that SOC stock dynamics did not follow a linear trend with time. After an initial SOC gain, a marked SOC loss particularly under perennial grasses could be observed (Figure 1c), followed by an increasing SOC pattern again. This pattern was also repeatedly observed for single sites with multiple observations (chronosequence), thus confirming this general observation. For depths 0–100 cm, a modest SOC gain during the 20-year period was discernible especially under perennial grasses (Figure 1d), although the temporal increment observed in the upper layers was not as clear and the number of studies was very limited (n = 10).

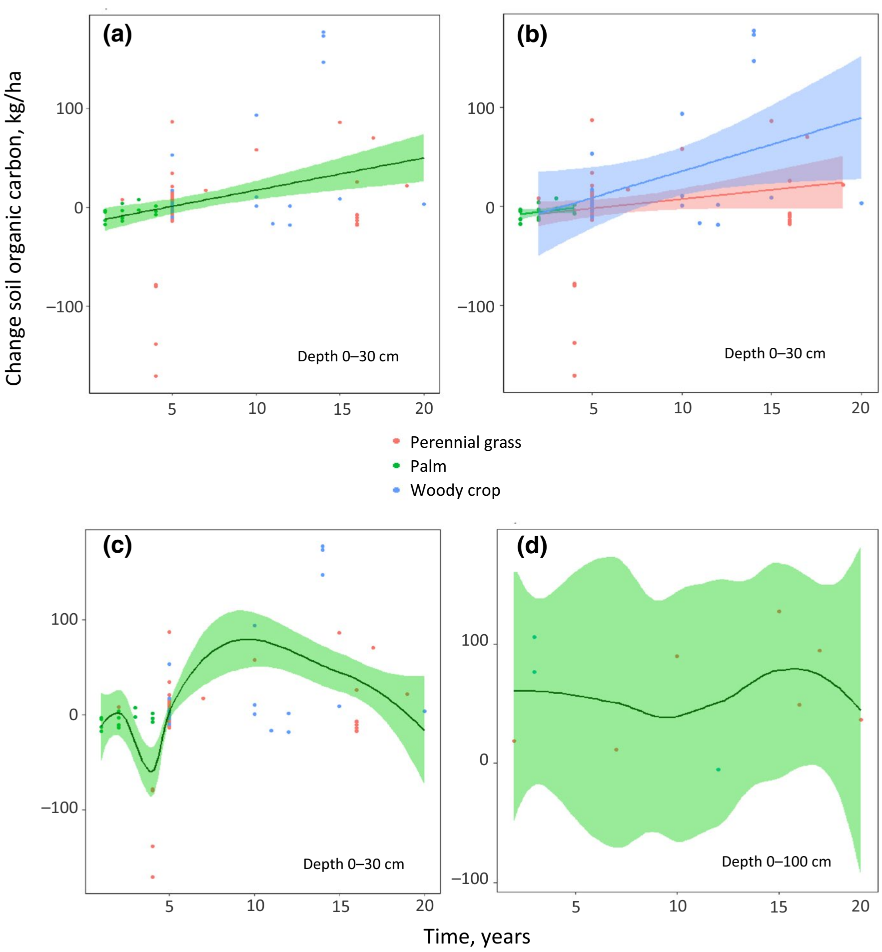

FIGURE 1 Empirical soil organic carbon (SOC) stock change values, in Mg/ha. Red, green, and blue dots are perennial grass, palm, and woody crop, respectively. (a) The green line is the linear trend of the mean value of SOC stock change including all the points (crop types) at depth 0–30 cm together, with the standard deviation in green shaded band. (b) The red, green, and blue lines are fitted linear models for perennial grasses, palms, and woody crop, respectively. (c) Actual empirical trend with the mean of SOC stock change as green line and the standard deviation of the mean in green shaded band, for depths 0–30 cm. (d) Actual empirical trend with the mean of SOC stock change as green line and the standard deviation of the mean in green shaded band, for depths 0–100 cm [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Modelling temporal changes in SOC, considering the effect of climate, soil properties, and land use

Temporal changes in SOC were modelled using the GLMM formulations with a Gaussian distribution (a list of all the fitted models can be found in Table S5):

$$\Delta \mathrm{SOC}_{\mathrm{rel}} = -2 + e^{\zeta} \quad (4)$$

where

$$\zeta = \frac{1}{100}\left(\begin{array}{l} 78.584 - 0.533\,\mathrm{Temp} - 0.189\,\mathrm{CropAge} - 0.018\,\mathrm{Depth} - 0.056 \\ \mathrm{PerClay} + 5.352\,\mathrm{BD} + |\mathrm{Previous\ land\ use}| + |\mathrm{Current\ land\ use}| \end{array}\right)$$

are the coefficients of the mean of the posterior fixed effects for: Temp, temperature, in Celsius; CropAge, the crop age (time since the crop was planted) in years; Depth, the profile depth in cm; PerClay, the percentage of clay; and BD, the soil bulk density. The coefficients for the mean posteriors of the random effects are given in Table 2.

The model explained 20% of the dataset variance, regardless of crop type. Although this means that a large proportion of the variance is not explained, this is, nonetheless, not a negligible percentage given the large heterogeneity in the data (including the different experimental methods, geographic regions, crop types, management practices, and ages) and the subsequently elevated Gaussian noise in the model. Of the explained variation, the main driver of the variation in SOC stock changes in perennial crops was temperature (Figure 2), which was negatively correlated with SOC changes. Crop age was second in importance, also negatively correlated with SOC change (Figure 2); changes in SOC were greater at the beginning of the crop establishment. Soil physical properties (BD, clay content) explained SOC changes to a lesser extent, with soils with greater BD and lower clay content showing greater changes in SOC. Depth and previous land use explained a minor proportion of the model variance, but these did improve the model fit (Table S5). Depth at the soil profile was negatively correlated with SOC changes, indicating that greater changes in SOC occurred at upper soil layers (Figure 2).

TABLE 2 Coefficients for the mean posteriors of the random effects of the ΔSOC empirical model

Previous land use			
Annual crop	Fallow	Grassland	Natural Forest
-5.431×10^{-05}	-2.178×10^{-05}	-2.832×10^{-04}	-2.733×10^{-04}
Current land use			
Agroforestry	Bioenergy grass	Food (and bio-products)	
-8.684×10^{-06}	-5.223×10^{-04}	5.647×10^{-04}	

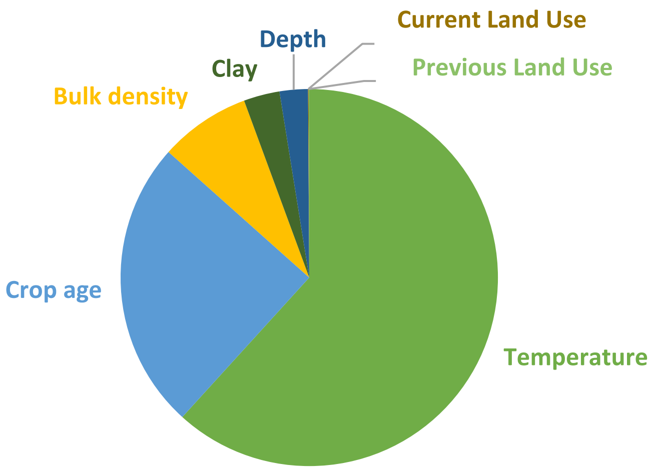

FIGURE 2 Percentage of variance explained by each of the soil organic carbon change model predictors. The previous land use categories are as follows: annual crop, fallow, grassland or natural forest; and the current land use ones: agroforestry, bioenergy grass or food, and bio-products [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

This study synthesizes the published, yet disparate, data on SOC changes at a global scale and provides for the first-time quantitative evidence about the effect of conversion to perennial crops on SOC relative to alternative land uses or cover types and over time. Specifically, it shows that a change from annual to perennial crops induces a SOC gain (Table 1) which indicates the potential to use perennials to sequester organic C across the cropland sector, especially where doing so has minimal trade-offs between SOC sequestration and food production. Besides, perennials increase the SOC stocks during crop life, at least up to 20 years (Figure 1). Climate, soil characteristics, and previous land use were identified as potential drivers of SOC dynamics in perennial crops at a global scale (Equation 4), with the average annual temperature playing a central role (Figure 2).

4.1 | Land conversion to perennial crops

A transition from an annual to a perennial to crop generally resulted in an average gain of a 20% (±10) in SOC (6.07 Mg/ha) after 20 years or more after conversion in the upper layers. In the 0–100 cm profile, the SOC gain was 11% (±8.5) a total of 5.66 Mg/ha in SOC. These slight differences between the 0–30 cm and 0–100 cm soil profile are partly likely due to the fact that the evaluated plots were different. If so, the information on the 30 upper centimeters is more reliable, since there are more data available (111 plots compared to 33). By contrast, a change from grassland to perennial crops appeared to cause a 1% loss of SOC in the top 30 cm the soil profile (although this is not statistical significant, therefore it should be taken with caution), the loss of SOC over 0–100 cm was more noticeable (−10%) and statistically significant. The effect of LUC from forest to perennials on SOC varied with the soil depth; where comparisons are restricted to the top 30 cm soil a 2% (16.8 Mg/ha) gain in SOC is observed (the value was not statistically significant, and should be considered only as indicative). But a substantial loss of SOC was observed and was statistically significant (−24% or −40 Mg/ha) when the comparison is extended to the top 100 cm (see also Don et al., 2011). These findings highlight that when evaluating LUC effects on SOC stocks, it is imperative to consider a greater proportion of the soil profile affected by the root system to gain a fuller picture of impacts.

While the finding that a change from any land use to annual crops results in a loss in SOC is consistent among studies (Deng et al., 2016; Don et al., 2011), the effect of a change from a natural ecosystem to a perennial crops plantation is not that clear. Don et al. (2011) found a decrease of 30% in SOC when converting forest to perennials. This finding is not fully consistent with our study, we found a loss of SOC at the top 100 cm (−24%) but no significant effect at the top 30 cm (Table 1).

4.2 | Factors influencing SOC temporal dynamics in perennial crops

The first factor identified to affect SOC changes was crop age, or time after perennial establishment. After the initial LUC disturbance, SOC under perennials increases over 20 years, at an average of 0.05 Mg ha^{-1} year^{-1} (Figure 1a) in the upper layers, 0–30 cm. This result is consistent with the patterns found in their analysis of SOC dynamics in perennial bioenergy crops in the upper soil layers by Ferchaud, Vitte, and Mary (2016). However, Ferchaud et al. (2016) observed a decrease in SOC in deeper horizons, which did not correspond to the findings in our evaluation. We observed that the increase in SOC is especially marked in woody crops where average gains of up to 0.1 Mg/ha (Figure 1b) were seen. However, this observed SOC gain was not constant: SOC increase was larger during the initial years after conversion to perennial crops after which a steady decline in SOC accumulation rate was observed (Figure 2c), consistent with the predictions of the GLMM (Equation 4). This supports the view that changes in SOC are greater at the beginning of the crop establishment and then decline until they reach a steady state (Smith, 2014). This pattern has also been observed in previous studies on SOC on perennial crops (Vicente-Vicente, García-Ruiz, Francaviglia, Aguilera, & Smith, 2016), and also reported for perennial woody crops in tropical savannas: In first cycle Eucalyptus plantations in Brazil, SOC losses after clearing of native vegetation were ascribed to decomposition of antecedent SOC at a faster pace than C was replenished in the young stands, but were reversed after harvest at age 7 years after planting and then by the ensuing coppice growth until age 14 years after planting (Zinn, Lal, & Resck, 2011).

Temperature and precipitation regimes are determining factors for the SOC balance, as they are strongly involved in processes responsible for both SOC inputs (i.e., litterfall production) and outputs (i.e., SOC decomposition, Davidson & Janssens, 2006). Therefore, differences in climate are probably one of the main causes explaining differences in SOC storage patterns among croplands in the world, as has been found for other ecosystems (Carvalhais et al., 2014; Doetterl et al., 2015). This study revealed temperature as one of the main factors affecting SOC changes in perennial crops globally (Figure 2, Equation 4). Temperature was negatively correlated with SOC changes, indicating that in warmer, tropical areas the relative change in SOC is lower than in temperate and boreal areas. We found temperature to be the main predictor of SOC changes over precipitation and over other climate indicators that combine temperature and precipitation together. This suggests that temperature exerts a stronger influence in soil respiratory processes than in plant growth and soil C input processes (which might be co-limited by other factors), thus limiting the potential for a more positive SOC balances in warm regimes. Soil physical properties were also significant in explaining SOC changes in the GLMM model: soils with greater values of BD showed greater changes in SOC, agreeing with the findings in Don et al. (2011), but this merely reflects the large weighting of BD in the calculation of SOC density. Soils with higher BD and lower SOC content are likely to have higher saturation deficit (Six, Conant, Paul, & Paustian, 2002)—the difference between maximum and minimum SOC that could be achieved—and thus may have higher potential to increase the SOC stocks (Vicente-Vicente, Gómez-Muñoz, Hinojosa-Centeno, Smith, & Garcia-Ruiz, 2017). The cultivated crop is a confounding factor in this study, and even with more data this limitation may remain, since some crops have a limited environmental range and are therefore only cultivated in certain climates. Nonetheless, woody crops showed a larger SOC gain on the whole than perennial grasslands (Figure 1).

In addition to the abovementioned factors, there are multiple, possibly interacting factors which affect SOC dynamics beyond the ones analyzed in this study, as indicated by the substantial unexplained variance in our data (Equation 4). Large variability among studies dealing with perennials has also been observed in previous studies (Aguilera et al., 2013; Vicente-Vicente et al., 2016). Some of the potential factors that are also likely to have impact and may improve the predictive capability of the model are management related: fertilizer application (type and rate), plant density, tillage, cover cropping, and other soil disturbances, but these could not be accounted for since there was not sufficient information across the dataset to model their effects. Along these lines, Vicente-Vicente et al. (2016) found that just by allowing the growth of spontaneous plant cover in the inter-row area and applying minimum tillage in Mediterranean orchards, an extra tonne of SOC per hectare and per year could be accumulated. Furthermore, the application of organic fertilizers and shredded pruning debris could increase this value by a factor of 3 to 4. The behavior of the perennial crop type in terms of above-ground biomass input production is also an important factor. Such as in Guava (*Psidium guajava*), leaf fall, bark fall, and also fruit falls in rainy season supply larger C input to soil in addition to the input from roots which helps in accumulation of 133 Mg/ha SOC stock in the top 2-m soil depth in a 31-year-old orchard situated in reclaimed sodic soil of northwest India (Datta, Basak, Chaudhari, & Sharma, 2015).

4.3 | SOC GLMM model caveats

The residuals from the GLMM showed an elevated Gaussian noise, but this was expected due to the large heterogeneity of the data, regarding experimental methods, biogeographic regions, crop types, and age among others. Yet, the predictors explained 20% of the dataset variance, across all crop types, indicating the difficultly associated with predictions of SOC at a global scale based on a purely empirical model with the currently available data. The available data are not only largely heterogeneous; in the light of our results, it becomes clear that more key information such as soil depth and management, which unfortunately are not always reported in studies (Aguilera et al., 2013).

We deliberately chose not to include crop type as a random effect, which indeed accounted for a notable proportion of the variance. There are two main reasons for this consideration; first, the intent was to derive a global/generic model to explain patterns of SOC changes under perennials, and not individual crop types. The dataset contains information on 58 crops at 709 locations (Ledo et al., 2019). Adding a random effect with 58 levels seems unreasonable. Second, and more importantly, many of the crops in the dataset were not duplicated (Ledo et al., 2019; Table S1), specifying crop type as random effect would be an obvious confounding factor.

The large heterogeneity of our dataset and neglecting some potentially important factors has not prevented us from revealing the robust observation that the SOC stocks under perennials are greater than under arable crops. In particular, we were not able to analyze changes in BD after and before perennials since those data were missing from the original dataset (see Ledo et al., 2019 for further details). We thus had to assume a fixed BD, while recommending that future experimental studies record BD before and after transition. Future data and studies might help to refine the estimates and regional distribution as driven by climatic, soil physico-chemical, and management differences across regions and crop types.

4.4 | Potential mechanisms of SOC accumulation in perennial crops

There are two ways of increasing C stock, either via increasing inputs or decreasing outputs. Soils that transition from annual to perennial crops may likely benefit from both: perennials produce more plant residues than annual crops (Ferchaud et al., 2016) and this extra organic matter consequently returns to the soil. Besides, soils under annual crops experience annual tillage or other frequent mechanical disturbances (Powlson et al., 2014), which allows faster decomposition of the SOC in upper layers. Perennials, in contrast, are disturbed usually only at the beginning of the life cycle and not during (Ledo et al., 2018), thus potentially avoiding SOC lost by mechanical soil treatments.

Perennials not only produce more plant residue than annual crops (Ferchaud et al., 2016) but also have the potential additional plant inputs from management interventions such us pruning and on-site retention of litter (Ledo et al., 2018). Rasse et al. (2005) assert that SOC is mainly derived from root C, from root exudates and fine root turnover. The fine root biomass, which typically has a fast turnover, is likely to be soon lost to the atmosphere as CO_2 (Glover, Culman, et al., 2010). However, perennial crops develop larger roots that penetrate and develop fine roots deeper in the soil. Root residues at deeper horizons are less subject to oxidation and thus more likely to remain as SOC in the soil. Additionally, root penetration changes soil texture (Reynolds, Bowman, Drury, Tan, & Lu, 2002) and thus potentially creates a larger and deeper rhizosphere which in turn may increase root exudates and thus soil microbial interactions (Huang et al., 2014), resulting in more C being captured in soil aggregates (Kutsch et al., 2009; Stockmann et al., 2013). In addition, the rhizomes of perennial grasses are known to be important contributors of organic matter and exudates to the soil (Zatta, Clifton-Brown, Robson, Hastings, & Monti, 2014), which would result in an increase in SOC.

The linear trend of SOC stock changes shows an increasing trend (Figure 1a). However, it can be seen that a minor SOC gain is followed by SOC loss for a period of a few years, and only after this does SOC start to consistently accumulate year-on-year (Figure 1c). This observed SOC gain has a subsequent levelling off of SOC accumulation rate and a decline when it stabilizes and reaches a steady state (Figure 1c), which is consistent with the acknowledged patterns of SOC accumulation (Smith, 2014), and also observed in agroforestry systems (Feliciano, Ledo, Hillier, & Nayak, 2018). This might be attributed to the so-called priming effect (Thiessen, Gleixner, Wutzler, & Reichstein, 2013; Wutzler & Reichstein, 2013), or to the disturbance produced when planting perennials (Smith, 2004) or a combination of both, since these are not mutually exclusive.

Another of the conclusions of our study is that the lack of annual soil disturbance contributes to SOC increase. The lack of frequent mechanical interventions may not only reduce SOC losses, but also C inputs to the soil may increase if the herbaceous layer is not removed. However, the soil of some woody cropping systems is kept permanently bare, and if this is the case, it reduces SOC even in no-till treatments (Aguilera et al., 2013). Furthermore, SOC protection mechanisms should also be considered. The physical protection (i.e., organic C within soil microaggregates) isolates the organic C from the activity of the soil microorganisms, preventing its mineralization. SOC physical protection is also affected by tillage (Vicente-Vicente et al., 2017), because of the disruption of the macroaggregates, precursors of soil microaggregates (Six, Bossuyt, Degryze, & Denef, 2004). This may be another mechanism that favors SOC accumulation under perennial crops, due to the lack of mechanical intervention. Another protection mechanism is chemical protection (Six et al., 2002). However, the chemical protection depends mainly on the chemical soil properties (e.g., pH) and, therefore, the management is supposed not to have a large effect on it and may not be a different between annual and perennial crops in this regard.

4.5 | Emission factor of LUC, potential of perennials as climate change mitigation tools, and food security allies

The IPCC (2014) guidelines for preparing GHG emissions inventories provide a default value of 1 as the relative stock change in SOC over a 20-year period in the top 30 cm after conversion from any land use to perennials crops (volume 4, section 5 croplands, tables 5.5 and 5.10), with an uncertainty of 50%. Results from this study suggest that this value can be refined to 1.12, since overall perennial crops accumulate SOC (Figure 1), leaving 50% uncertainty to be conservative. To be more precise, it should be 1.12 for woody plants and 1.06 for perennial grasses (Figure 2; Appendix S1). Furthermore, this study revealed a relative stock change of 1.2 in the case of a change from annual to perennial crop (Table 1). This is not, strictly speaking, a change in land use, since the land use is arable in both cases. However, as the 1.2 value is relevant and important, we suggest that a subcategory may be added and considered in further assessments and recommendations. Similarly, the default value from grasslands and forest would be 1, since we did not find significant differences (Table 1).

A second recommendation for GHG factors and C stock benchmarks is to consider using a soil profile of 0–100 cm depth in future assessments. This study highlights the importance of the SOC stocks stored deeper than 30 cm. This considering only the top 30 cm may favor practices and crops which concentrate SOC in the top 30 cm rather than sequester C across a more relevant profile.

Overall, perennial crops accumulate SOC through time (Figure 1), and a change from annual to perennial crop will lead to a SOC increase during at least 20 years (Table 1). Furthermore, perennial crops have been suggested as a tool to increase food security and ecosystem functioning (Glover, Reganold, et al., 2010). Aside from increasing SOC stocks, perennials could also contribute to reducing soil erosion (Glover, Culman, et al., 2010), and with the potentiality to contribute to food security improvement (Lal, 2004). A significant reduction in soil erosion has been reported when the main crop is accompanied by a cover crop and thus bare soil is avoided (Aguilera et al., 2013; Gómez et al., 2011). A second important climate change mitigation option in perennial crops is adding crop residues back to the ground; perennials produce more plant residues than annual crops (Ferchaud et al., 2016) which inputs extra organic C to the soil. Alongside, bioenergy crops aside from being climate change mitigation tools in the field by increasing SOC (Dondini et al., 2009; Robertson et al., 2017), they usually have an overall GHG reduction benefit favorable when compared with other crops (Whitaker et al., 2018), and also they bring an extra GHG reduction when they are used to replace fossil fuels and may thus contribute to the transition to a low C economy (Qin et al., 2016).

Perennial crops have therefore the potential to be a climate change mitigation, by resulting a negative C balance system or at least storing some C in the ground and thus reducing atmospheric CO_2 concentration. Nonetheless there are some important limitations and the C gain cannot be considered as a universal statement and recipe for C sequestration by itself. Additionally, while some management practices such as reduced- or no-tillage may reduce SOC losses, additional agricultural practices may be required so the full life cycle needs to be considered (Schlesinger & Amundson, 2019). Plant residue management is also important, that is, burning tress at the end of the crop cycle results in net GHG emissions (Ledo et al., 2018). In this case, the C stored in the ground during the perennial plantation may be lower than the C and other GHGs emitted during the combustion, thus resulting in net positive emissions from the plantation. In contrast, using perennials in restoration of degraded agricultural lands, either on their own or in agroforestry combination, can provide additional benefits via coproducts, thus potentially contributing to food security and local economies.

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CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHOR CONTRIBUTION

A.L., J.H., and P.S. initiated and designed the study. A.L. performed the analyses. H.B. participated in the empirical model fitting and diagnosis. E.D.-P. contributed to the further development of the initial study. A.Z. helped writing the first draft. A.L., P.S., A.Z., J.W., J.L.V.-V., Z.Q., N.P.M., Y.L.Z., M.Ll., M.Li., M.K., M.D., A.D., E.D.-P., A.D., H.B., E.A., and J.H. (all the authors) contributed ideas and wrote the manuscript.

DATA AVAILABILITY STATEMENT

The data and programming code used in this study are reproduced in Data S1 of this article. The original database—including details on data gathering and harmonization—is published in Ledo et al. (2019).

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REFERENCES

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

Blagodatsky, S., & Smith, P. (2011). Soil physics meets soil biology: Towards better mechanistic prediction of greenhouse gas emissions from soil. *Soil Biology and Biochemistry*, *47*, 78–92. https://doi.org/10.1016/j.soilbio.2011.12.015

Carvalhais, N., Forkel, M., Khomik, M., Bellarby, J., Jung, M., Migliavacca, M., … Reichstein, M. (2014). Global covariation of carbon turnover times with climate in terrestrial ecosystems. *Nature*, *514*(7521), 213–217. https://doi.org/10.1038/nature13731

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. C., … Vieilledent, G. (2015). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, *20*(10), 3177–3190. https://doi.org/10.1111/gcb.12629

Cox, T. S., Glover, J. D., Van Tassel, D. L., Cox, C. M., & DeHaan, L. R. (2006). Prospects for developing perennial grain crops. *BioScience*, https://doi.org/10.1641/0006-3568(2006)56[649:PFDPGC]2.0.CO;2

Crowther, T. W., Todd-Brown, K. E. O., Rowe, C. W., Wieder, W. R., Carey, J. C., Machmuller, M. B., … Bradford, M. A. (2016). Quantifying global soil carbon losses in response to warming. *Nature*, *540*(7631), 104–108. https://doi.org/10.1038/nature20150

Datta, A., Basak, N., Chaudhari, S. K., & Sharma, D. K. (2015). Soil properties and organic carbon distribution under different land uses in reclaimed sodic soils of North-West India. *Geoderma Regional*, *4*, 134–146. https://doi.org/10.1016/j.geodrs.2015.01.006

Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, *440*(7081), 165–173. https://doi.org/10.1038/nature04514

Deng, L., Zhu, G., Tang, Z., & Shangguan, Z. (2016). Global patterns of the effects of land-use changes on soil carbon stocks. *Global Ecology and Conservation*, *5*, 127–138. https://doi.org/10.1016/j.gecco.2015.12.004

Doetterl, S., Stevens, A., Six, J., Merckx, R., Van Oost, K., Pinto, M. C., … Boeckx, P. (2015). Soil carbon storage controlled by interactions between geochemistry and climate. *Nature Geoscience*, *8*(10), 780–783. https://doi.org/10.1038/ngeo2516

Don, A., Böhme, I. H., Dohrmann, A. B., Poeplau, C., & Tebbe, C. C. (2017). Microbial community composition affects soil organic carbon turnover in mineral soils. *Biology and Fertility of Soils*, *53*(4), 445–456. https://doi.org/10.1007/s00374-017-1198-9

Don, A., Schumacher, J., & Freibauer, A. (2011). Impact of tropical land-use change on soil organic carbon stocks – A meta-analysis. *Global Change Biology*, *17*(4), 1658–1670. https://doi.org/10.1111/j.1365-2486.2010.02336.x

Dondini, M., Hastings, A., Saiz, G., Jones, M. B., & Smith, P. (2009). The potential of *Miscanthus* to sequester carbon in soils: Comparing field measurements in Carlow, Ireland to model predictions. *GCB Bioenergy*, *1*(6), 413–425. https://doi.org/10.1111/j.1757-1707.2010.01033.x

Feliciano, D., Ledo, A., Hillier, J., & Nayak, D. R. (2018). Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? *Agriculture, Ecosystems & Environment*, *254*, 117–129. https://doi.org/10.1016/j.agee.2017.11.032

Ferchaud, F., Vitte, G., & Mary, B. (2016). Changes in soil carbon stocks under perennial and annual bioenergy crops. *GCB Bioenergy*, *8*(2), 290–306. https://doi.org/10.1111/gcbb.12249

Fialho, R., & Zinn, Y. (2014). Changes in soil organic carbon under eucalyptus plantations in Brazil: A comparative analysis. *Land Degradation & Development*, *25*(5), 428–437. https://doi.org/10.1002/ldr.2158

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., … Gibbs, H. K. (2005). Global consequences of land use. *Science*, *309*(5734), 570–574. https://doi.org/10.1126/science.1111772

Glover, J. D., Culman, S. W., DuPont, S. T., Broussard, W., Young, L., Mangan, M. E., … Buckley, D. H. (2010). Harvested perennial grasslands provide ecological benchmarks for agricultural sustainability. *Agriculture, Ecosystems & Environment*, *137*(1-2), 3–12. https://doi.org/10.1016/j.agee.2009.11.001

Glover, J. D., Reganold, J. P., Bell, L. W., Borevitz, J., Brummer, E. C., Buckler, E. S., … Xu, Y. (2010). Increased food and ecosystem security via perennial grains. *Science*, *328*(5986), 1638–1639. https://doi.org/10.1126/science.1188761

Gómez, J. A., Llewellyn, C., Basch, G., Sutton, P. B., Dyson, J. S., & Jones, C. A. (2011). The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. *Soil Use and Management*, *27*(4), 502–514. https://doi.org/10.1111/j.1475-2743.2011.00367.x

Huang, X.-F., Chaparro, J. M., Reardon, K. F., Zhang, R., Shen, Q., & Vivanco, J. M. (2014). Rhizosphere interactions: Root exudates, microbes, and microbial communities. *Botany-Botanique*, *92*(4), 267–275. https://doi.org/10.1139/cjb-2013-0225

IPCC. (2014). *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: Author.

IPCC. (2019). *IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Author. Retrieved from https://www.ipcc.ch/report/SRCCL/

Kutsch, W. L., Bahn, M., & Heinemeyer, A. (2009). *Soil carbon dynamics: An integrated methodology*. Cambridge, UK: Cambridge University Press.

Laganiere, J., Angers, D. A., & Pare, D. (2010). Carbon accumulation in agricultural soils after afforestation: A meta-analysis. *Global Change Biology*, *16*(1), 439–453. https://doi.org/10.1111/j.1365-2486.2009.01930.x

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development*, *17*(2), 197–209. https://doi.org/10.1002/ldr.696

Ledo, A., Heathcote, R., Hastings, A., Smith, P., & Hillier, J. (2018). Perennial-GHG: A new generic allometric model to estimate biomass accumulation and greenhouse gas emissions in perennial food and bioenergy crops. *Environmental Modelling and Software*, *102*, 292–305. https://doi.org/10.1016/j.envsoft.2017.12.005

Ledo, A., Hillier, J., Smith, P., Aguilera, E., Blagodatskiy, S., Brearley, F. Q., … Zerihun, A. (2019). A global, empirical, harmonised dataset of soil organic carbon changes under perennial crops. *Scientific Data*, *6*(1). https://doi.org/10.1038/s41597-019-0062-1

Paustian, K., Six, J., Elliott, E. T., & Hunt, H. W. (2000). Management options for reducing CO_2 emissions from agricultural soils. *Biogeochemistry*, *48*, 147–163. https://doi.org/10.1023/A:1006271331703

Poeplau, C., Vos, C., & Don, A. (2017). Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. *Soil*, *3*(1), 61–66. https://doi.org/10.5194/soil-3-61-2017

Post, W. M., & Kwon, K. C. (2000). Soil carbon sequestration and land-use change: Processes and potential. *Global Change Biology*, *6*(3), 317–327. https://doi.org/10.1046/j.1365-2486.2000.00308.x

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., & Cassman, K. G. (2014). Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change*, *4*(8), 678–683. https://doi.org/10.1038/nclimate2292

Qin, Z., Dunn, J. B., Kwon, H., Mueller, S., & Wander, M. M. (2016). Soil carbon sequestration and land use change associated with biofuel production: Empirical evidence. *GCB Bioenergy*, *8*(1), 66–80. https://doi.org/10.1111/gcbb.12237

Rasse, D. P., Rumpel, C., & Dignac, M.-F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant and Soil*, *269*(1-2), 341–356. https://doi.org/10.1007/s11104-004-0907-y

Reynolds, W. D., Bowman, B. T., Drury, C. F., Tan, C. S., & Lu, X. (2002). Indicators of good soil physical quality: Density and storage parameters. *Geoderma*, *110*(1-2), 131–146. https://doi.org/10.1016/S0016-7061(02)00228-8

Robertson, A. D., Whitaker, J., Morrison, R., Davies, C. A., Smith, P., & Mcnamara, N. P. (2017). A *Miscanthus* plantation can be carbon neutral without increasing soil carbon stocks. *GCB Bioenergy*, *9*(3), 645–661. https://doi.org/10.1111/gcbb.12397

Rue, H., Martino, S., & Chopin, N. (2009). Approximate Bayesian inference for latent Gaussian models by using integrated nested Laplace approximations. *Journal of the Royal Statistical Society: Series B*, *71*(2), 319–392. https://doi.org/10.1111/j.1467-9868.2008.00700.x

Schlesinger, W. H., & Amundson, R. (2019). Managing for soil carbon sequestration: Let's get realistic. *Global Change Biology*, *25*(2), 386–389. https://doi.org/10.1111/gcb.14478

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, *79*(1), 7–31. https://doi.org/10.1016/j.still.2004.03.008

Six, J., Conant, R., Paul, E., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, *241*, 155–176. https://doi.org/10.1023/A:1016125726789

Smith, P. (2004). Soils as carbon sinks: The global context. *Soil Use and Management*, *20*(2), 212–218. https://doi.org/10.1111/j.1475-2743.2004.tb00361.x

Smith, P. (2014). Do grasslands act as a perpetual sink for carbon? *Global Change Biology*, *20*(9), 2708–2711. https://doi.org/10.1111/gcb.12561

Smith, P., Gregory, P. J., Van Vuuren, D., Obersteiner, M., Havlík, P., Rounsevell, M., … Bellarby, J. (2010). Competition for land. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 2941–2957. https://doi.org/10.1098/rstb.2010.0127

Stockmann, U., Adams, M. A., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., … Zimmermann, M. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment*, *164*, 80–99. https://doi.org/10.1016/j.agee.2012.10.001

Thiessen, S., Gleixner, G., Wutzler, T., & Reichstein, M. (2013). Both priming and temperature sensitivity of soil organic matter decomposition depend on microbial biomass – An incubation study. *Soil Biology and Biochemistry*, *57*, 739–748. https://doi.org/10.1016/j.soilbio.2012.10.029

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

Vicente-Vicente, J. L., Gómez-Muñoz, B., Hinojosa-Centeno, M. B., Smith, P., & Garcia-Ruiz, R. (2017). Carbon saturation and assessment of soil organic carbon fractions in Mediterranean rainfed olive orchards under plant cover management. *Agriculture, Ecosystems & Environment*, *245*, 135–146. https://doi.org/10.1016/j.agee.2017.05.020

Whitaker, J., Field, J. L., Bernacchi, C. J., Cerri, C. E. P., Ceulemans, R., Davies, C. A., … McNamara, N. P. (2018). Consensus, uncertainties and challenges for perennial bioenergy crops and land use. *GCB Bioenergy*, *10*(3), 150–164. https://doi.org/10.1111/gcbb.12488

Wollenberg, E., Tapio-Bistrom, M.-L., Grieg-Gran, M., & Nihart, A. (Eds.). (2011). *Climate change mitigation and agriculture*. Oxon: Earthscan. ISBN 9781849713924.

Wutzler, T., & Reichstein, M. (2013). Priming and substrate quality interactions in soil organic matter models. *Biogeosciences*, *10*(3), 2089–2103. https://doi.org/10.5194/bg-10-2089-2013

Zatta, A., Clifton-Brown, J., Robson, P., Hastings, A., & Monti, A. (2014). Land use change from C3 grassland to C4 *Miscanthus*: Effects on soil carbon content and estimated mitigation benefit after six years. *GCB Bioenergy*, *6*(4), 360–370. https://doi.org/10.1111/gcbb.12054

Zinn, Y. L., Lal, R., & Resck, D. V. (2011). Eucalypt plantation effects on organic carbon and aggregation of three different-textured soils in Brazil. *Soil Research*, *49*(7), 614. https://doi.org/10.1071/SR11264

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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