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LETTER

Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems

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Supplementary material for this article is available online

Abstract

Agroforestry systems comprise trees and crops, or trees and pastures within the same field. Globally, they cover approximately 1 billion hectares of land and contribute to the livelihoods of over 900 million people. Agroforestry systems have the capacity to sequester large quantities of carbon (C) in both soil and biomass. However, these systems have not yet been fully considered in the approach to C accounting developed by the Intergovernmental Panel on Climate Change, largely due to the high diversity of agroforestry systems and scarcity of relevant data. Our literature review identified a total of 72 scientific, peer-reviewed articles associated with biomass C storage (50) and with soil organic carbon (SOC) (122), containing a total of 542 observations (324 and 218, respectively). Based on a synthesis of the reported observations, we are presenting a set of Tier 1 coefficients for biomass C storage for each of the eight main agroforestry systems identified, including alley cropping, fallows, hedgerows, multistrata, parklands, shaded perennial-crop, silvoarable and silvopastoral systems, disaggregated by climate and region. Using the same agroforestry classification, we are presenting a set of stock change factors (F_{LU}) and SOC accumulation/loss rates for three main land use changes (LUCs): cropland to agroforestry; forest to agroforestry; and grassland to agroforestry. Globally, the mean SOC stock change factors ($\pm$ confidence intervals) were estimated to be 1.25 $\pm$ 0.04, 0.89 $\pm$ 0.07, and 1.19 $\pm$ 0.10, for the three main LUCs, respectively. However, these average coefficients hide huge disparities across and within different climates, regions, and types of agroforestry systems, highlighting the necessity to adopt the more disaggregated coefficients provided herein. We encourage national governments to synthesize data from local field experiments to generate country-specific factors for more robust estimation of biomass and SOC storage.

Introduction

According to FAO (2016), agriculture is still the main global driver of deforestation. More precisely, commercial agriculture is the main driver, followed by subsistence agriculture (Hosonuma *et al* 2012). Deforestation is the main source of anthropogenic greenhouse gases (GHGs) emissions from the Agriculture, Forestry and Other Land Use (AFOLU) sector. For the last decade (2007–2016), emissions from Land Use Change (LUC), including deforestation, are estimated at 1.3 $\pm$ 0.7 Gt C yr^{-1} (Le Quéré *et al* 2018). Meeting the world's increasing demand for food and other land-based products, without additional deforestation, will require productive landscapes that are managed sustainably (FAO 2009, 2016), accompanied by a modification of diets and a reduction of waste (Smith 2013, Smith *et al* 2013). Increasing the presence of multipurpose systems, such as agroforestry systems, is part of the solution (Paustian *et al* 2016).

Agroforestry systems are complex agro-ecosystems combining trees and crops, or trees and pastures, within the same field (Nair 1993). Agroforestry is a generic term that includes a wide variety of systems, varying by tree and crop species arrangements as a function of the climate zone and region, rendering the classification of agroforestry systems challenging (Nair 1985, Somarriba 1992, Torquebiau 2000). Agroforestry systems can build soil fertility, prevent soil erosion, enhance biodiversity and largely contribute to the resilience of farming systems through the provision of ecosystem services, such as the diverse set of tree products, such as fodder, fuelwood, food and building materials.

The benefit of agroforestry systems in terms of climate change regulation is widely recognized (Albrecht and Kandji 2003), with recent syntheses (Kumar and Nair 2011, Lorenz and Lal 2014) and meta-analyses (Chatterjee *et al* 2018, de Stefano and Jacobson 2018, Feliciano *et al* 2018, Shi *et al* 2018) reiterating their positive impact on SOC sequestration and global and national carbon C budgets (Zomer *et al* 2016). Agroforestry systems also have an important role to play in adaptation to climate change due to their contribution to enhanced water use, storage and efficiency, improved microclimate, and diversified income and food sources (Lasco *et al* 2014).

Despite the suite of socioeconomic and environmental benefits associated with agroforestry systems, they are not widely recognized as such within the scientific community and are only eligible for payment of ecosystem services, under the Clean and Development Mechanisms, if compliant with the definition of afforestation and reforestation activities (UNFCCC 2013, 2015). Indeed, the complexity of agroforestry systems renders the estimation of their impact on GHG fluxes challenging (Nair 2012). The capacity of soils and biomass in agroforestry systems to store C depends on several factors, including local pedoclimatic conditions, previous land-use, tree density and species, harvesting and pruning practices and management activities. In general, the transition from an agriculture system to an agroforestry system is beneficial to SOC, while the conversion of secondary or primary forests to agroforestry systems leads to SOC losses (de Stefano and Jacobson 2018, Feliciano *et al* 2018).

The IPCC Good Practice Guidance (Penman *et al* 2003) and National GHG Inventory Guidelines (NGHGI) (IPCC 2006) provide recommendations on methods and default estimates for assessing C stocks and emissions at three tiers of detail, ranging from Tier 1 (with average emission/stock change factors for large eco-regions of the world and globally-available data, simplest to use) up to Tier 3 (with high resolution methods specific for each country and repeated through time). According to IPCC (2006) Guidelines for NGHGIs, agroforestry systems are classified under the category 'perennial crops', which comprises gathered trees and shrubs, in combination with herbaceous crops (e.g. agroforestry) or orchards, vineyards and plantations such as cocoa, coffee, tea, oil palm, coconut, rubber trees, and bananas. As a result of insufficient data, agroforestry is classified as a perennial crop.

Under the IPCC 'perennial crops' category, a set of average sequestration rates per climate type are proposed. The aboveground biomass growth rate was estimated at 10 t C ha^{-1} yr^{-1} for tropical wet, 2.6 t C ha^{-1} yr^{-1} for tropical moist, 1.8 t C ha^{-1} yr^{-1} for tropical dry, and 2.1 t C ha^{-1} yr^{-1} for all temperate climates (IPCC 2006). A high level of uncertainty was attributed to these factors (standard error range of ±75% in all climates), which represent the coefficients to estimate aboveground biomass carbon storage across all perennial and agroforestry systems, regardless of their diversity. The same knowledge gap is also observed in the global biomass C map, where cultivated and managed lands are given a fixed biomass C value of 5 tC ha^{-1}, with no distinction for agroforestry systems (Ruesch and Gibbs 2008). No coefficients have been proposed yet for SOC sequestration in agroforestry systems.

The objectives of the paper is to (i) propose more accurate Tier 1 emission factors for aboveground and belowground biomass C sequestration by climate and region for different agroforestry systems and (ii) propose response ratio (or management factors) and Tier 1 emission factors for SOC sequestration by LUC, climate and region for different agroforestry systems.

Materials and methods

Literature search and data extraction

We conducted a literature review of available studies that estimated SOC stocks (or the information necessary to calculate them, i.e. SOC content and bulk density), and/or biomass C stocks. The research process included use of several research engines and knowledge platforms, namely ISI—Web of Knowledge, Google Scholar, and Scopus. A key-word search was performed using the following keys: biomass OR soil AND ('carbon stock*' OR 'carbon pool*' OR 'carbon sequestration' OR 'carbon concentration') AND (agroforest* OR parkland* OR homegarden OR multistrata OR hedgerow OR windbreak OR shelterbelt OR 'live fence' OR 'tree intercrop*' OR silvo*arable OR silvo*pasture OR 'rotation* wood*' OR tree*fallow* OR (tree* AND 'improve* fallow*') OR (tree* AND relay*crop*) OR (tree* AND alley*crop*)).

Several parameters were deemed necessary for the data to be contained in the database, specifically: the previous land use, the depth of measurement and the time frame over which the LUC had occurred should be reported. In addition, studies also had to provide the location or climate data of the study sites in order to classify the data by climate regimes according to the IPCC guidelines (IPCC 2007). If the required data were not present in the text or in tables, data were extracted from graphs using the WebPlotDigitizer software. In the case that a study included multiple sites, they were treated as separate data points. In general, only data from primary sources were collected in the database. If data from a review of primary sources were included in the database, the data were only reported once.

As a result of this systematic literature review, we collected data from a collection of 50 peer reviewed studies that reported biomass C storage and 72 studies that reported SOC stock changes in agroforestry systems. In total, 324 and 218 observations were obtained for biomass and SOC storage, respectively. The full database is available in appendix 1 and 2, available online at stacks.iop.org/ERL/13/124020/mmedia.

Changes in SOC stocks

In general, the majority of selected publications reported SOC stock and only a few used the equivalent soil mass approach. In the case that the SOC concentration and bulk density were reported, the SOC stock was calculated. Only six publications did not report bulk densities, which were estimated using the mean bulk density per soil type as proposed by Batjes (1996).

In the case that both a synchronic (SOC stocks measured in the agroforestry and in an adjacent control plot) and diachronic (SOC stocks measured in the same plot before and after LUC) approaches were presented for the same site, the priority was given to the diachronic approach as the one most widely considered among the scientific literature as reliable (Costa Junior *et al* 2013). In the case that SOC stocks were presented at different periods of time, only one date was identified in order to avoid dependency of observations and priority was given to the most recent measurements as SOC stock changes are usually not detected during the first several years due to measurement uncertainties (Smith 2004). In the case that SOC stocks were measured at different depths, only the value measured at 0–30 cm was taken into account. If stocks were only measured at 0–20 and 0–40 cm, the deepest depth (0–40 cm) was considered because it included the ploughed horizon and most tree and crop roots. If only one depth was available but did not correspond to 0–30 cm, the observations was still considered.

Two different methods were applied to calculate SOC storage or loss rates (figure 1). The first one (equation (1)), used by the IPCC (2006) for the Tier 1 method, is a stock change factor (F_{LU}, dimensionless). It indicates a relative change in SOC stocks in the new land use compared to the previous one. It is also called a response ratio (Ogle *et al* 2004, 2005), or management factor (Maia *et al* 2013). F_{LU} higher than 1 correspond to a SOC storage, while F_{LU} lower than 1 correspond to a SOC loss.

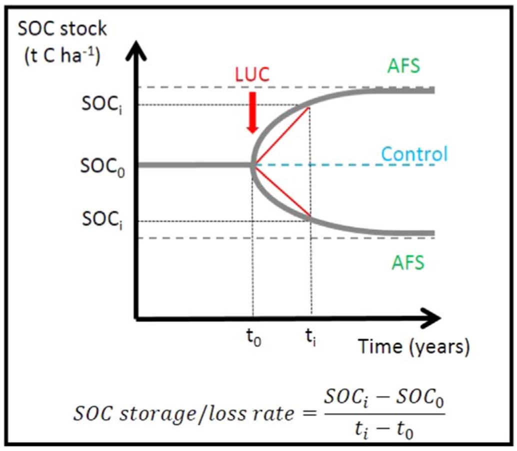

Figure 1. Calculation of SOC storage/loss rates for the different land use changes (LUC). The different Land Use Changes were: Cropland to Agroforestry, Control = Cropland (N = 158); Forest to Agroforestry, Control = Forest (N = 29); Grassland to Agroforestry, Control = Grassland (N = 28); Plantation to Agroforestry, Control = Plantation (N = 3). AFS: Agroforestry systems.

$$F_{LU} = \frac{Agroforestry\ SOC\ stock}{Control\ SOC\ stock}. \quad (1)$$

The second method (equation (2)) was used to estimate absolute changes in SOC stocks. SOC storage/loss rates (t C ha^{-1} yr^{-1}) were then calculated using the following formula (figure 2):

$$SOC\ storage/loss\ rate = \frac{Agroforestry\ SOC\ stock - Control\ SOC\ stock}{Age}, \quad (2)$$

where SOC stocks are expressed in t C ha^{-1}, and the age corresponded to the agroforestry age in years.

Annual biomass increment

If only biomass was reported in a study, the carbon fraction (CF) of dry matter of 0.47 was applied to convert it into a carbon stock (IPCC 2006).

The root:shoot ratio (R) is defined as the ratio of belowground biomass to aboveground biomass and is the primary method used by nations to estimate below ground biomass and C stocks for NGHGIs (Mokany *et al* 2006). In the case that the root:shoot ratio was not empirically-derived, default estimates for perennial woody vegetation recommended by IPCC (2006) were used for each climatic zone: 0.27 in Boreal, 0.26 in Temperate, and 0.24 in Tropical (Cairns *et al* 1997).

Agroforestry classification

The different types of agroforestry systems considered in this manuscript are presented in table 1. This classification is adapted from Nair *et al* (2009) where the same term 'alley cropping' was used for very different agroforestry systems in tropical and temperate regions. In this study, we make a distinction between tropical alley cropping, which involve dense

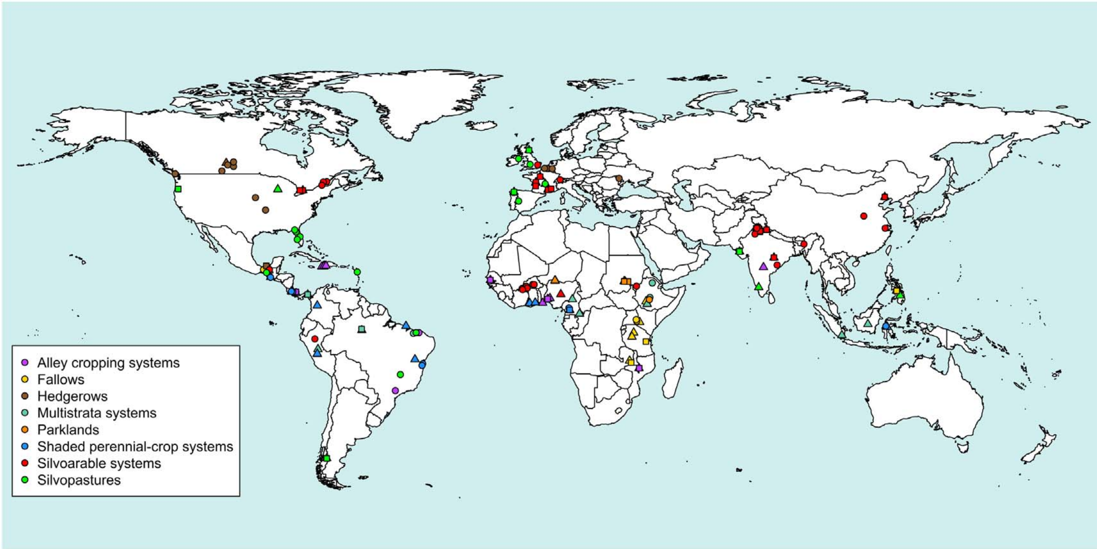

Figure 2. Sites of published studies on SOC (circles) and biomass (triangles) storage in various agroforestry systems. A few studies reported both SOC and biomass (squares). See footnotes of tables 2 and 3 for the full list of publications.

Table 1. Description of major agroforestry types (adapted from Nair *et al* (2009).

Type of agroforestry system	Definition
Alley cropping	Fast-growing, usually leguminous, woody species (mainly shrubs) grown in crop fields, usually at high densities. The woody species are regularly pruned and the prunings are applied as mulch into the alleys as a source of organic matter and nutrients. Usually found in tropical regions. Sometimes referred as 'intercropping systems'.
Fallows	Only sequential agroforestry system considered here. Include both improved and natural fallows.
Hedgerows	They consist of linear plantation around the fields. They include also shelterbelts, windbreaks and live fences.
Multistrata systems	Multistorey combinations of a large number of various trees at high density, and perennial and annual crops. They include home gardens and agroforests.
Parklands	Intercropping of agricultural crops or grazing land under low density mature scattered trees. Typical of dry areas like Sahel (e.g. *Faidherbia albida*).
Shaded perennial-crop systems	Growing shade-tolerant species such as cacao and coffee under, or in between, overstorey shade trees that can be used for timber or other commercial tree products.
Silvoarable systems	Woody species planted in parallel tree rows to allow mechanization and intercropped with an annual crop; usually used for timber (e.g. *Juglans* spp), but also for fuel (e.g. *Populus* spp). Usually low tree density per hectare. Usually found in temperate regions, but not exclusively.
Silvopastures	Woody species planted on permanent grasslands, often grazed.

alleys of fast-growing, usually leguminous woody species, and temperate silvoarable systems, which contain a low numbers of trees, usually for timber, in rows spaced widely enough to allow for mechanization (table 1).

Data analysis

Four main land conversions were studied for SOC storage/loss, cropland to agroforestry, forest to agroforestry, grassland to agroforestry, and plantation to agroforestry. Four publications also reported conversion from abandoned cropland to agroforestry (Diels *et al* 2004, Swamy and Puri 2005, Baumert *et al* 2016, Bright *et al* 2017). These abandoned croplands are defined as former long-term croplands uncropped (natural fallow) a couple of years before the establishment of the agroforestry system. Due to insufficient data, they were included in the category 'cropland to agroforestry'. The effect of the previous land use on annual biomass increment rates was considered negligible (IPCC 2006).

All the graphs and statistical analyses were performed using R software version 3.1.1 (R Development Core Team 2013), at a significance level of <0.05.

Results

Data on SOC stocks were collected in 31 countries, plus 4 US states, 4 Canadian provinces and in one French overseas department (figure 2, appendix 1). Data on aboveground biomass were obtained from 33 different countries, plus 1 US state, and 3 Canadian provinces (figure 2, appendix 2).

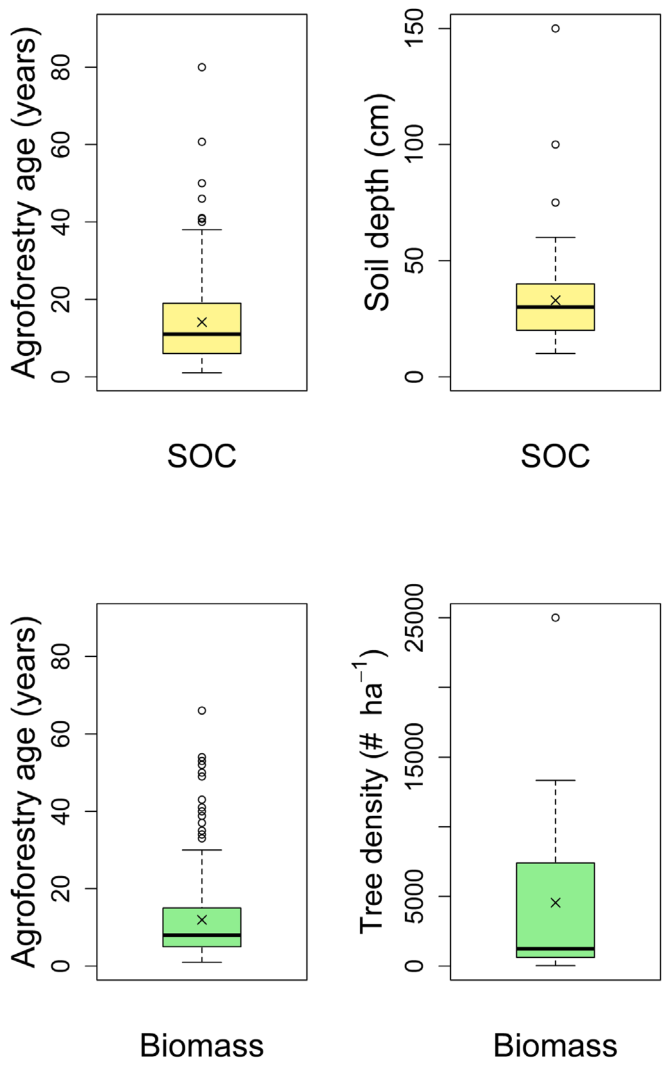

Figure 3. Distribution of site ages (years) and soil depth (cm) in the SOC and biomass databases. Upper and lower edges of boxes indicate 75th and 25th percentiles, horizontal lines within boxes indicate median, whiskers below and above the boxes indicate the 10th and 90th percentiles, and crosses indicate means. Outliers are plotted as individual points.

In the SOC database, the median and mean age of the agroforestry systems were 11.0 and 14.1 years, respectively, while the median and mean soil depth were 30.0 and 32.9 cm (figure 3). In the biomass database, the median and mean age of the agroforestry systems were 8.0 and 12.0 years, respectively, while the median and mean tree density were 1250 and 4533 trees ha^{-1} (figure 3).

The mean SOC storage rate ($\pm$ confidence intervals) for croplands converted to agroforestry systems was 0.75 $\pm$ 0.19 t C ha^{-1} yr^{-1}, while the mean SOC loss rate for forests converted to agroforestry systems was -1.15 ± 1.02 t C ha^{-1} yr^{-1}, all regions, climates, and agroforestry systems taken together (figure 4). Mean SOC change rates for the conversion from grasslands to agroforestry systems was not significantly different from zero (0.23 $\pm$ 0.25 t C ha^{-1} yr^{-1}). The mean stock change factors ($\pm$ confidence intervals) were 1.25 $\pm$ 0.04, 0.89 $\pm$ 0.07, 1.19 $\pm$ 0.10, for croplands converted to agroforestry, forests to agroforestry, and grassland to agroforestry, respectively (figure 4).

The response ratio (F_{LU}) and SOC storage/loss rates for different land use conversions to agroforestry systems are presented per climate type and region in table 2. Aboveground biomass sequestration rates are presented in table 3.

Discussion

Land use conversion to agroforestry systems

In general, conversion from croplands to agroforestry systems resulted in increased SOC stock but with large variation. A few studies however reported a SOC loss (Baumert *et al* 2016), but with no clear explanation as to the driver. It could be due to soil disturbance during tree planting, followed by an erosive event. The SOC storage rate depends on various agroforestry system characteristics, such as tree density, age and species but also on management factors (Kim *et al* 2016), including pruning, soil tillage and fertilization (Feliciano *et al* 2018). Initial conditions such as SOC stock in the previous cropland, and local pedoclimatic factors

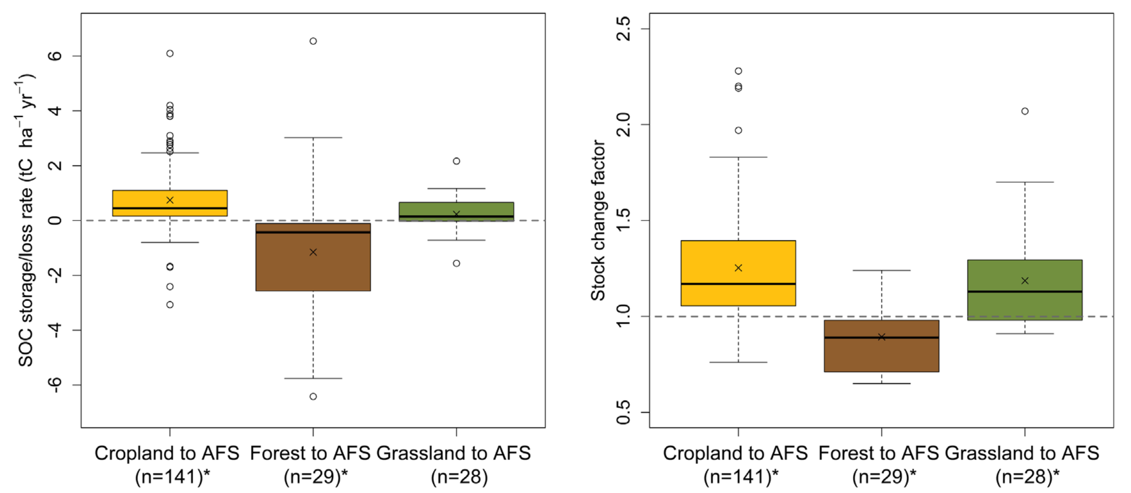

Figure 4. Soil organic carbon (SOC) storage/loss rates and stock change factors (F_{LU}) for different land uses converted to agroforestry systems. AFS: AgroForestry Systems. All climates and types of agroforestry systems are mixed in this graph. Upper and lower edges of boxes indicate 75th and 25th percentiles, horizontal lines within boxes indicate median, whiskers below and above the boxes indicate the 10th and 90th percentiles, and crosses indicate mean SOC storage rate per type of subsystem. Outliers are plotted as individual points. *represents SOC storage rates significantly different from 0 ($P \leqslant 0.05$).

(e.g. rainfall, soil texture) are also important drivers of SOC storage (Corbeels *et al* 2018, Feliciano *et al* 2018). However, the amount of C input to the soil is probably one of the main factor explaining increased SOC stocks in croplands converted to agroforestry (Cardinael *et al* 2018, Fujisaki *et al* 2018).

Conversion from forests to agroforestry systems generally induced SOC loss. This result confirms recent findings (Chatterjee *et al* 2018, de Stefano and Jacobson 2018, Feliciano *et al* 2018, Shi *et al* 2018). However, the loss is usually less than if forests were converted to croplands (Schmitt-Harsh *et al* 2012, Norgrove and Hauser 2013). Globally, conversion from grasslands to agroforestry systems did not improve SOC stocks. This result is in accordance with Poeplau *et al* (2011) who found no difference in SOC stocks of afforested grasslands in Europe, and with Fujisaki *et al* (2015) who found slightly higher SOC stocks in grasslands than in forests. However, we did not explore here the effect of the grassland management on SOC storage. Converting degraded grasslands to silvopastures could increase SOC stocks (Mangalassery *et al* 2014).

Challenges in estimating SOC stock changes in agroforestry systems

As pointed out by Nair (2012), there is a significant lack of rigorous data on C sequestration in agroforestry systems. To assess changes in SOC stock and storage/loss following a LUC, some basic data are required: a description of the previous land use, SOC stocks or SOC content and bulk densities in both the previous and new land use, soil depth considered, and time span since conversion. Unfortunately, the literature review showed that these basic data were not always present. The concerned papers were therefore not used to estimate the new emission factors. Many authors have, for instance, measured SOC in agroforestry but not in a reference system, preventing assessment of whether soil had lost or gained organic C (Pandey *et al* 2000, Roshetko *et al* 2002, Isaac *et al* 2005, Mungai *et al* 2006, Muñoz *et al* 2007, Singh and Sharma 2007, Smiley and Kroschel 2008, Saha *et al* 2009, Labata *et al* 2012, Seddaiu *et al* 2013, Simón *et al* 2013, Guimarães *et al* 2014, Sitzia *et al* 2014, Nath *et al* 2015, Ramos *et al* 2018, Sun *et al* 2018). Some publications compared SOC stocks in agroforestry and in a « reference » system, but this reference system was different from the land use present before conversion to agroforestry (Drechsel *et al* 1991, Materechera and Mkhabela 2001, Isaac *et al* 2003, Nyamadzawo *et al* 2008, Takimoto *et al* 2008, Howlett *et al* 2011b, Cardinael *et al* 2012, Gelaw *et al* 2014, Jacobi *et al* 2014, Ehrenbergerová *et al* 2016, Rajab *et al* 2016). This could be very problematic, such as when a forest is converted to either a shaded-perennial crop system or a monocrop plantation. Comparing SOC stocks in the agroforestry and in the plantation could result in an apparent SOC storage, while in reality the conversion of the forest to the agroforestry system usually leads to a loss in SOC.

The age of the agroforestry system or the time span since conversion from a previous land use is also often missing in most studies, making it impossible to estimate the rate of change in SOC stock (Kater *et al* 1992, Kessler 1992, Walter *et al* 2003, Wade *et al* 2010, Labata *et al* 2012, Alvarado *et al* 2013, Simón *et al* 2013, Frazão *et al* 2014, Goswami *et al* 2014, Rocha *et al* 2014, Sitzia *et al* 2014, Baah-Acheamfour *et al* 2015, Jadan *et al* 2015, Asase and Tetteh 2016, Tumwebaze and Byakagaba 2016). Several articles only reported SOC content, and bulk densities were missing (Drechsel *et al* 1991, Mazzarino *et al* 1993, Chander *et al* 1998, Kang *et al* 1999, Kaur *et al* 2000, Pandey *et al* 2000, Singh and Sharma 2007, Kumar *et al* 2010,

Table 2. Response ratio (F_{LU}) and SOC storage/loss rates per climate type and region for different land use conversions to agroforestry systems. SOC storage rates for hedgerows are presented per kilometer of hedgerows, not per hectare of agricultural field. The tree density represents total tree density of the agroforestry system, including perennial crops (coffee, cacao) in the case of shaded perennial and multistrata systems. For hedgerows, tree density is presented per kilometer of hedgerows. N: number of observations; SD: standard deviation; CI: confidence interval; Min: minimum observed SOC storage rate; Max: maximum observed SOC storage rate. Ab. Cropland: Abandoned Cropland (former cropland uncultivated (natural fallow) for a couple of years before conversion to agroforestry).

Climate			Tree density	Response ratio (F_{LU})				SOC storage/loss rate			
			(# ha^{-1})					(tC ha^{-1} yr^{-1})			
Region	Land use change	N	Mean ± SD	Mean ± SD	95% CI	Min	Max	Mean ± SD	95% CI	Min	Max
Cool temperate ($n = 35$)											
Asia	Cropland to Silvoarable	2	833 ± 0	1.05 ± 0.11	—	0.97	1.12	0.24 ± 0.49	—	−0.11	0.59
Europe	Cropland to Hedgerow	4	125 ± 0	1.41 ± 0.20	0.19	1.22	1.65	0.68 ± 0.34	0.36	0.26	0.99
	Cropland to Silvoarable	1	99	1.05	—	—	—	0.51	—	—	—
	Grassland to Silvopasture	5	260 ± 134	1.08 ± 0.14	0.13	0.92	1.28	0.19 ± 0.41	0.18	−0.27	0.76
North America	Cropland to Hedgerow	6	546 ± 373	1.24 ± 0.10	0.08	1.15	1.41	0.67 ± 0.23	0.18	0.37	1.02
	Cropland to Silvoarable	16	231 ± 149	1.08 ± 0.22	0.11	0.76	1.77	0.19 ± 1.54	0.75	−3.07	4.20
South America	Grassland to Silvopasture	1	400	1.09	—	—	—	0.93	—	—	—
All regions	Cropland to Hedgerow	10	406 ± 363	1.30 ± 0.16	0.10	1.15	1.65	0.67 ± 0.26	10	0.26	1.02
	Cropland to Silvoarable	19	287 ± 238	1.08 ± 0.20	0.09	0.76	0.77	0.21 ± 1.41	0.63	−3.07	4.20
	Grassland to Silvopasture	6	283 ± 133	1.08 ± 0.13	0.10	0.92	1.28	0.31 ± 0.48	0.38	−0.27	0.93
Warm temperate ($n = 32$)											
Asia	Cropland to Silvoarable	7	333 ± 121	1.40 ± 0.22	0.16	1.02	1.68	1.33 ± 1.47	1.09	0.14	3.80
Europe	Cropland to Hedgerow	8	125 ± 0	1.11 ± 0.22		0.94	1.62	0.15 ± 0.23	0.16	−0.14	0.51
	Cropland to Silvoarable	6	88 ± 50	1.12 ± 0.17	0.13	1.01	1.45	0.28 ± 0.16	0.13	0.10	0.46
	Cropland to Silvopasture	4	1667 ± 962	1.17 ± 0.13	0.13	1.03	1.35	1.93 ± 1.54	1.51	0.38	4.05
	Grassland to Silvopasture	2	35	1.03 ± 0.16	0.22	0.92	1.14	−0.34 ± 0.54	—	−0.72	0.05
North America	Cropland to Hedgerow	3	1111	1.16 ± 0.14	0.16	1.05	1.32	0.52 ± 0.72	0.81	0.10	1.35
	Grassland to Hedgerow	1	1333	1.14	—	—	—	0.68	—	—	—
	Grassland to Silvopasture	1	571	0.94	—	—	—	−0.60	—	—	—
All regions	Cropland to Hedgerow	11	235 ±329	1.13 ± 0.19	0.11	0.94	1.62	0.25 ± 0.41	0.24	−0.14	1.35
	Cropland to Silvoarable	13	220 ± 156	1.27 ± 0.24	0.13	1.01	1.68	0.85 ± 1.18	0.64	0.10	3.80
	Cropland to Silvopasture	4	1667 ± 962	1.17 ± 0.13	0.13	1.03	1.35	1.93 ± 1.54	1.51	0.38	4.05
	Grassland to Hedgerow	1	1333	1.14	—	—	—	0.68	—	—	—
	Grassland to Silvopasture	3	303 ± 379	1.00 ± 0.12	0.14	0.92	1.14	−0.42 ± 0.41	0.47	−0.72	0.05
Temperate (all) ($n = 67$)											
	Cropland to Hedgerow	21	320± 347	1.21 ± 0.20	0.08	0.94	1.65	0.45 ± 0.40	0.17	−0.14	1.35
	Cropland to Silvoarable	32	260 ± 208	1.16 ± 0.23	0.08	0.76	1.77	0.47 ± 1.34	0.46	−3.07	4.20
	Cropland to Silvopasture	4	1667 ± 962	1.17 ± 0.13	0.13	1.03	1.35	1.93 ± 1.54	1.51	0.38	4.05
	Grassland to Hedgerow	1	1333	1.14	—	—	—	0.68	—	—	—

Table 2. (Continued.)

Climate			Tree density	Response ratio (F_{LU})				SOC storage/loss rate ($tC\,ha^{-1}\,yr^{-1}$)			
Region	Land use change	N	($\#\,ha^{-1}$) Mean ± SD	Mean ± SD	95% CI	Min	Max	Mean ± SD	95% CI	Min	Max
	Grassland to Silvopasture	9	288 ± 182	1.05 ± 0.13	0.08	0.92	1.28	0.07 ± 0.57	0.37	−0.72	0.93
Tropical dry ($n = 68$)											
Africa	Cropland to Alley cropping	6	2999 ± 3107	1.63 ± 0.15	0.12	1.36	1.83	0.49 ± 0.49	0.39	0.16	1.14
	Cropland to Fallow	19	10 000 ± 0	1.40 ± 0.24	0.11	1.04	1.97	0.99 ± 0.59	0.27	0.11	2.52
	Cropland to Silvoarable	10	726 ± 436	1.06 ± 0.14	0.09	0.81	1.28	0.36 ± 1.57	0.98	−2.41	3.89
	Grassland to Parkland	5	198 ± 78	1.15 ± 0.18	0.16	0.98	1.44	0.07 ± 0.08	0.07	−0.03	0.19
Asia	Cropland to Silvoarable	22	518 ± 233	1.23 ± 0.22	0.09	0.96	1.80	0.92 ± 1.48	0.62	−0.08	6.10
	Grassland to Silvopasture	4	278 ± 0	1.44 ± 0.18	0.18	1.30	1.70	0.48 ± 0.16	0.16	0.33	0.69
South America	Forest to Alley cropping	1	200	0.67	—	—	—	−4.91	—	—	—
	Forest to Silvopasture	1	260	0.93	—	—	—	−1.00	—	—	—
All regions	Cropland to Alley cropping	6	2999 ± 3107	1.63 ± 0.15	0.12	1.36	1.83	0.49 ± 0.49	0.39	0.16	1.14
	Cropland to Fallow	19	10 000 ± 0	1.40 ± 0.24	0.11	1.04	1.97	0.99 ± 0.59	0.27	0.11	2.52
	Cropland to Silvoarable	32	589 ± 326	1.17 ± 0.21	0.07	0.81	1.80	0.74 ± 1.51	0.52	−2.41	6.10
	Forest to Alley cropping	1	200	0.67	—	—	—	−4.91	—	—	—
	Forest to Silvopasture	1	260	0.93	—	—	—	−1.00	—	—	—
	Grassland to Parkland	5	198 ± 78	1.15 ± 0.18	0.16	0.98	1.44	0.07 ± 0.08	0.07	−0.03	0.19
	Grassland to Silvopasture	4	278 ± 0	1.44 ± 0.18	0.18	1.30	1.70	0.48 ± 0.16	0.16	0.33	0.69
Tropical moist ($n = 47$)											
Africa	Cropland to Alley cropping	12	8148 ± 2735	1.25 ± 0.23	0.13	0.98	1.65	0.21 ± 0.12	0.07	−0.04	0.34
	Forest to Shaded Perennial	2	1397 ± 73	1.09 ± 0.19	—	0.95	1.22	0.07 ± 0.25	—	−0.11	0.24
Asia	Cropland to Alley cropping	4	4000 ± 0	1.47 ± 0.17	0.17	1.28	1.67	1.92 ± 0.74	0.73	1.12	2.78
	Cropland to Fallow	3	—	1.13 ± 0.16	0.18	0.96	1.27	0.75 ± 1.31	1.48	−0.75	1.68
	Cropland to Hedgerow	2	40 000 ± 0	1.17 ± 0.09	—	1.10	1.23	0.60 ± 0.33	—	0.37	0.83
	Cropland to Silvoarable	1/2	859 ± 357	1.08	—	—	—	1.32 ± 1.27	—	0.42	2.21
Central America	Cropland to Fallow	2	998 ± 85	1.00 ± 0.14	—	0.90	1.10	−0.60 ± 1.51	—	−1.67	0.47
	Cropland to Silvoarable	1	425	1.19	—	—	—	2.91	—	—	—
	Grassland to Silvopasture	3	12 000 ± 0	1.25 ± 0.32	0.36	0.91	1.54	0.97 ± 1.32	1.49	−0.44	2.17
North America	Grassland to Silvopasture	4	—	1.33 ± 0.50	0.49	0.98	2.07	0.19 ± 0.31	0.30	−0.02	0.64
South America	Cropland to Alley cropping	1	—	1.09	—	—	—	1.01	—	—	—
	Cropland to Multistrata	2	—	2.24 ± 0.06	—	2.19	2.28	3.14 ± 0.95	—	2.47	3.81
	Forest to Shaded Perennial	6	1220 ± 444	1.07 ± 0.17	0.14	0.87	1.24	1.60 ± 2.65	2.12	−0.34	6.55
	Forest to Silvopasture	2	250 ± 0	1.01 ± 0.04	—	0.98	1.03	1.30 ± 2.45	—	−0.43	3.03

Table 2. (Continued.)

Climate			Tree density	Response ratio (F_{LU})				SOC storage/loss rate ($\text{tC ha}^{-1}\,\text{yr}^{-1}$)			
Region	Land use change	N	($\#\,\text{ha}^{-1}$) Mean ± SD	Mean ± SD	95% CI	Min	Max	Mean ± SD	95% CI	Min	Max
	Grassland to Shaded Perennial	1	1233	0.95	—	—	—	−1.56	—	—	—
All regions	Cropland to Alley cropping	17	16 111 ± 14 436	1.29 ± 0.23	0.11	0.98	1.67	0.79 ± 0.91	0.49	−0.04	2.78
	Cropland to Fallow	5	998 ± 85	1.08 ± 0.15	0.13	0.90	1.27	0.21 ± 1.40	1.23	−1.67	1.68
	Cropland to Hedgerow	2	4000 ± 0	1.17 ± 0.09	—	1.10	1.23	0.60 ± 0.33	—	0.37	0.83
	Cropland to Multistrata	2	—	2.24 ± 0.06	—	2.19	2.28	3.14 ± 0.95	—	2.47	3.81
	Cropland to Silvoarable	2/3	714 ± 356	1.14 ± 0.08	0.09	1.08	1.19	1.85 ± 1.28	1.45	0.42	2.91
	Forest to Shaded Perennial	8	1264 ± 385	1.07 ± 0.16	0.11	0.87	1.24	1.21 ± 2.35	1.63	−0.34	6.55
	Forest to Silvopasture	2	250 ± 0	1.01 ± 0.04	—	0.98	1.03	1.30 ± 2.45	—	−0.43	3.03
	Grassland to Shaded Perennial	1	1233	0.95	—	—	—	−1.56	—	—	—
	Grassland to Silvopasture	7	12 000 ± 0	1.29 ± 0.40		0.91	2.07	0.52 ± 0.89	0.66	−0.44	2.17
Tropical montane (n = 20)											
Africa	Cropland to Fallow	0/2	—	—	—	—	—	0.39 ± 0.02	—	0.37	0.40
	Cropland to Multistrata	8	—	1.35 ± 0.41	0.28	0.95	2.20	1.21 ± 1.04	0.72	−0.17	2.77
	Forest to Parkland	10	5 ± 0	0.74 ± 0.08	0.05	0.65	0.89	−3.67 ± 2.09	1.29	−6.42	−0.88
Tropical wet (n = 16)											
Africa	Forest to Shaded Perennial	1	1477	0.99				−0.01	—	—	—
Asia	Forest to Shaded Perennial	2	—	0.76 ± 0.14	0.20	0.66	0.86	−1.23 ± 0.71	—	−1.73	−0.72
Central America	Cropland to Alley cropping	5	2222 ± 1521	1.19 ± 0.15	0.14	1.04	1.38	0.90 ± 0.86	0.77	0.26	2.34
	Forest to Multistrata	1	—	1.00	—	—	—	0.00	—	—	—
	Forest to Shaded Perennial	1	10 102	0.85	—	—	—	−0.17	—	—	—
	Grassland to Hedgerow	1	1110	1.11	—	—	—	0.80	—	—	—
	Plantation to Shaded Perennial	3	1019 ± 641	1.07 ± 0.06	0.07	1.01	1.13	0.61 ± 0.52	0.59	0.13	1.17
South America	Forest to Multistrata	1	577	0.96	—	—	—	−0.26	—	—	—
	Forest to Silvoarable	1	—	0.95	—	—	—	−0.26	—	—	—
All regions	Cropland to Alley cropping	5	2222 ± 1521	1.19 ± 0.15	0.14	1.04	1.38	0.90 ± 0.86	0.77	0.26	2.34
	Forest to Multistrata	2	577	0.98 ± 0.03	0.04	0.96	1.00	−0.13 ± 0.18	—	−0.26	0.00
	Forest to Shaded Perennial	4	5790 ± 6099	0.84 ± 0.14	0.13	0.66	0.99	−0.66 ± 0.77	0.76	−1.73	−0.01
	Forest to Silvoarable	1	—	0.95	—	—	—	−0.26	—	—	—
	Grassland to Hedgerow	1	1110	1.11	—	—	—	0.80	—	—	—
	Plantation to Shaded Perennial	3	1019 ± 641	1.07 ± 0.06	0.07	1.01	1.13	0.61 ± 0.52	0.59	0.13	1.17
Tropical (all) (n = 151)											
	Cropland to Alley cropping	28	10 625 ± 12 960	1.35 ± 0.25	0.09	0.98	1.83	0.67 ± 0.75	0.28	−0.04	2.78

Table 2. (Continued.)

Climate			Tree density	Response ratio (F_{LU})				SOC storage/loss rate ($tC\ ha^{-1}\ yr^{-1}$)			
Region	Land use change	N	(# ha^{-1}) Mean ± SD	Mean ± SD	95% CI	Min	Max	Mean ± SD	95% CI	Min	Max
	Cropland to Fallow	24/26	8875 ± 3075	1.34 ± 0.26	0.10	0.90	1.97	0.79 ± 0.83	0.32	−1.67	2.52
	Cropland to Hedgerow	2	4000 ± 0	1.17 ± 0.09	—	1.10	1.23	0.60 ± 0.33	—	0.37	0.83
	Cropland to Multistrata	10	—	1.53 ± 0.52	0.32	0.95	2.28	1.59 ± 1.27	0.79	−0.17	3.81
	Cropland to Silvoarable	34/35	601 ± 325	1.17 ± 0.21	0.07	0.81	1.80	0.84 ± 1.50	0.50	−2.41	6.10
	Forest to Alley cropping	1	200	0.67	—	—	—	−4.91	—	—	—
	Forest to Multistrata	2	577	0.98 ± 0.03	0.04	0.96	1.00	−0.13 ± 0.18	—	−0.26	0.00
	Forest to Parkland	5	5 ± 0	0.74 ± 0.08	0.07	0.65	0.84	−2.64 ± 1.94	1.70	−5.58	−0.88
	Forest to Shaded Perennial	12	2169 ± 2809	1.00 ± 0.19		0.66	1.24	0.59 ± 2.13	1.20	−1.73	6.55
	Forest to Silvoarable	1	—	0.95	—	—	—	−0.26	—	—	—
	Forest to Silvopasture	3	253 ± 6	0.98 ± 0.05	0.06	0.93	1.03	0.53 ± 2.18	2.47	−1.00	3.03
	Grassland to Hedgerow	1	1110	1.11	—	—	—	0.80	—	—	—
	Grassland to Parkland	5	198 ± 78	1.15 ± 0.18	0.16	0.98	1.44	0.07 ± 0.08	0.07	−0.03	0.19
	Grassland to Shaded Perennial	1	1233	0.95	—	—	—	−1.56	—	—	—
	Grassland to Silvopasture	11	4185 ± 6053	1.34 ± 0.33	0.20	0.91	2.07	0.50 ± 0.70	0.41	−0.44	2.17
	Plantation to Shaded Perennial	3	1019 ± 641	1.07 ± 0.06	0.07	1.01	1.13	0.61 ± 0.52	0.59	0.13	1.17

a. Based on information from the following studies:1)Land Use Change = Cropland to Agroforestry; Control = Cropland Adhikary *et al* (2017), Bambrick *et al* (2010), Baumert *et al* (2016), Benbi *et al* (2012), Bertalot *et al* (2014), Bright *et al* (2017), Cardinael *et al* (2015a), Cardinael *et al* (2017), Chander *et al* (1998), Chauhan *et al* (2010), de Lima *et al* (2011), Dhillon & Van Rees (2017), Diels *et al* (2004), Fernández-Núñez *et al* (2010), Gupta *et al* (2009), Kang *et al* (1999), Kaonga & Coleman (2008), Kaur *et al* (2000), Kimaro *et al* (2011), Lasco & Suson (1999), Lenka *et al* (2012), Lu *et al* (2015), Maikhuri *et al* (2000), Makumba *et al* (2007), Mao *et al* (2012), Mazzarino *et al* (1993), Oelbermann *et al* (2004), Oelbermann *et al* (2006), Pardon *et al* (2017), Peichl *et al* (2006), Raddad *et al* (2006), Ramesh *et al* (2015), Rimhanen *et al* (2016), Sauer *et al* (2007), Seitz *et al* (2017), Singh & Gill (2014) Soto-Pinto *et al* (2010), Swamy & Puri (2005), Thiel *et al* (2015), Upson & Burgess (2013), Verchot *et al* (2011), Wang *et al* (2015), Wiesmeier *et al* (2018), Winans *et al* (2014), Winans *et al* (2016), Wotherspoon *et al* (2014). 2)Land Use Change = Forest to Agroforestry; Control = Forest Alegre & Rao (1996), Demessie *et al* (2013), Gama-Rodrigues *et al* (2010), Hertel *et al* (2009), Kirby & Potvin (2007), Maia *et al* (2007), Monroe *et al* (2016), Nijmeijer *et al* (2018), Norgrove & Hauser (2013), Schmitt-Harsh *et al* (2012), Schroth *et al* (2002), Singh *et al* (2010), Tonucci *et al* (2011) .3)Land Use Change = Grassland to Agroforestry; Control = Grassland Abaker *et al* (2016), Beckert *et al* (2016), Cardinael *et al* (2017), Dube *et al* (2012), Fornara *et al* (2018), Haile *et al* (2008), Howlett *et al* (2011a), Mangalassery *et al* (2014), Monroe *et al* (2016), Paudel *et al* (2012), Sharrow & Ismail (2004), Sierra & Nygren (2005), Soto-Pinto *et al* (2010), Upson *et al* (2016), Villanueva-López *et al* (2015) .4)Land Use Change = Plantation to Agroforestry; Control = Plantation Beer *et al* (1990), Hergoualc'h *et al* (2012).

Table 3. Aboveground and belowground biomass increment rates for different agroforestry systems per climate type and regions. Biomass storage rates and tree density for hedgerows are presented per kilometer of hedgerows, not per hectare of agricultural field. The tree density represents total tree density of the agroforestry system, including perennial crops (coffee, cacao) in the case of shaded perennial and multistrata systems. N: number of observations; ABG: aboveground; BLG: belowground; SD: standard deviation; CI: confidence interval; min: minimum observed SOC storage rate; Max: maximum observed SOC storage rate.

Climate region	Agroforestry system	N	Tree density (# ha^{-1})	ABG biomass storage rate (tC ha^{-1} yr^{-1})				BLG biomass storage rate (tC ha^{-1} yr^{-1})			
			Mean ± SD	Mean ± SD	95% CI	Min	Max	Mean ± SD	95% CI	Min	Max
Cool temperate (n = 27)											
Asia	Silvoarable	2	833 ± 0	2.97 ± 0.02	—	2.96	2.98	0.77 ± 0.00	—	0.77	0.78
Europe	Silvopasture	4	225 ± 126	2.17 ± 1.05	1.03	1.12	3.17	0.56 ± 0.28	0.27	0.29	0.83
North America	Hedgerow	12	816 ± 853	0.87 ± 0.75	0.42	0.31	3.15	0.23 ± 0.19	0.11	0.08	0.82
	Silvoarable	7	111 ± 0	0.59 ± 0.23	0.17	0.40	0.99	0.14 ± 0.04	0.03	0.09	0.22
	Silvopasture	1	571	0.97	—	—	—	0.11	—	—	—
South America	Silvopasture	1	400	1.18	—	—	—	0.52	—	—	—
All regions	Hedgerow	12	400 ± 0	0.87 ± 0.75	0.42	0.31	3.15	0.23 ± 0.19	0.11	0.08	0.82
	Silvoarable	9	271 ± 318	1.12 ± 1.07	0.70	0.40	2.98	0.28 ± 0.28	0.18	0.09	0.78
	Silvopasture	6	312 ± 175	1.81 ± 0.99	0.80	0.97	3.17	0.48 ± 0.28	0.23	0.11	0.83
Warm temperate (n = 9)											
Europe	Silvoarable	5	76 ± 38	0.52 ± 0.60	0.53	0.00	1.48	0.14 ± 0.15	0.13	0.00	0.37
	Silvopasture	4	1667 ± 962	3.11 ± 2.88	2.82	0.73	7.16	1.03 ± 1.01	0.99	0.21	2.44
Temperate (*all*) (n = 36)											
	Hedgerow	12	816 ± 853	0.87 ± 0.75	0.42	0.31	3.15	0.23 ± 0.19	0.11	0.08	0.82
	Silvoarable	14	202 ± 269	0.91 ± 0.91	0.50	0.00	2.98	0.23 ± 0.25	0.13	0.00	0.78
	Silvopasture	10	854 ± 903	2.33 ± 1.94	1.20	0.73	7.16	0.70 ± 0.68	0.42	0.11	2.44
Tropical dry (n = 101)											
Africa	Alley cropping	20	1000 ± 0	1.88 ± 1.21	0.53	0.42	4.53	0.45 ± 0.29	0.13	0.10	1.09
	Fallow	22	—	5.61 ± 2.78	1.16	2.32	11.33	2.54 ± 2.28	0.95	0.56	10.40
	Hedgerow	2	1667 ± 471	0.48 ± 0.18	—	0.36	0.61	0.12 ± 0.04	0.06	0.09	0.15
	Multistrata	3	2771 ± 1413	1.63 ± 0.38	0.43	1.19	1.91	0.46 ± 0.11	0.12	0.33	0.53
	Parkland	7	152 ± 102	0.59 ± 0.46	0.34	0.22	1.54	0.21 ± 0.11	0.08	0.10	0.38
Asia	Alley cropping	15	10 430 ± 2746	2.79 ± 1.35	0.68	1.09	5.81	0.67 ± 0.32	0.16	0.26	1.40
	Fallow	9	1250 ± 0	5.61 ± 5.05	3.30	1.22	17.43	0.53 ± 0.24	0.16	0.17	0.95
	Silvoarable	6	540 ± 98	6.24 ± 2.77	2.22	3.59	9.71	1.62 ± 0.68	0.54	0.81	2.41
	Silvopasture	17	1609 ± 938	3.07 ± 3.99	2.02	0.06	13.21	0.84 ± 1.02	0.49	0.02	3.26
All regions	Alley cropping	35	5041 ± 5052	2.27 ± 1.33	0.44	0.42	5.81	0.54 ± 0.32	0.11	0.10	1.40
	Fallow	31	1250 ± 0	5.61 ± 3.50	1.23	1.22	17.43	1.95 ± 2.13	0.75	0.17	10.40
	Hedgerow	2	5833 ± 1179	0.48 ± 0.18	—	0.36	0.61	0.12 ± 0.04	0.06	0.09	0.15
	Multistrata	3	2771 ± 1413	1.63 ± 0.38	0.43	1.19	1.91	0.46 ± 0.11	0.12	0.33	0.53

Table 3. (Continued.)

Climate region	Agroforestry system	N	Tree density (# ha^{-1})	ABG biomass storage rate (tC ha^{-1} yr^{-1})				BLG biomass storage rate (tC ha^{-1} yr^{-1})			
			Mean ± SD	Mean ± SD	95% CI	Min	Max	Mean ± SD	95% CI	Min	Max
	Parkland	7	152 ± 102	0.59 ± 0.46	0.34	0.22	1.54	0.21 ± 0.11	0.08	0.10	0.38
	Silvoarable	6	540 ± 98	6.24 ± 2.77	2.22	3.59	9.71	1.62 ± 0.68	0.54	0.81	2.41
	Silvopasture	17	1609 ± 938	3.07 ± 3.99	1.90	0.06	13.21	0.84 ± 1.02	0.49	0.02	3.26
Tropical moist (n = 97)											
Africa	Alley cropping	28	7233 ± 1805	2.75 ± 1.63	0.60	0.30	6.58	0.59 ± 0.38	0.14	0.07	1.58
	Multistrata	3	1902 ± 1253	2.98 ± 0.74	0.84	2.15	3.58	0.72 ± 0.18	0.20	0.52	0.86
	Shaded Perennial	5	—	1.82 ± 0.71	0.62	0.63	2.38	0.44 ± 0.17	0.15	0.15	0.57
	Silvoarable	5	—	5.09 ± 2.27	1.99	1.35	6.76	1.22 ± 0.54	0.48	0.32	1.62
Asia	Fallow	1	—	5.30	—	—	—	1.27	—	—	—
	Multistrata	21	628 ± 247	3.03 ± 2.09	0.89	0.42	9.29	0.73 ± 0.50	0.21	0.10	2.23
	Shaded Perennial	2	1481 ± 0	2.07 ± 0.54	—	1.69	2.45	0.50 ± 0.13	—	0.41	0.59
	Silvoarable	11	1065 ± 152	1.50 ± 1.12	0.66	0.64	4.61	0.35 ± 0.27	0.16	0.15	1.11
Central America	Alley cropping	15	25 000 ± 0	2.28 ± 1.04	0.52	0.45	4.41	0.55 ± 0.25	0.13	0.11	1.06
South America	Shaded Perennial	6	4131 ± 779	3.06 ± 2.51	2.01	1.07	7.64	0.71 ± 0.57	0.46	0.26	1.76
All regions	Alley cropping	43	13 733 ± 8781	2.59 ± 1.45	0.43	0.30	6.58	0.58 ± 0.34	0.11	0.07	1.68
	Fallow	1	—	5.30	—	—	—	1.27	—	—	—
	Multistrata	24	802 ± 634	3.02 ± 1.96	0.78	0.42	9.29	0.73 ± 0.47	0.19	0.10	2.23
	Shaded Perennial	13	3071 ± 1552	2.43 ± 1.79	0.97	0.63	7.64	0.57 ± 0.40	0.22	0.15	1.76
	Silvoarable	16	1065 ± 152	2.63 ± 2.27	1.11	0.64	6.76	0.62 ± 0.55	0.27	0.15	1.62
Tropical montane (n = 30)											
Africa	Fallow	30	7521 ± 4182	3.12 ± 1.31	0.47	0.56	6.35	1.12 ± 0.74	0.26	0.14	4.50
Tropical wet (n = 60)											
Africa	Fallow	3	—	6.21 ± 2.92	3.31	2.90	8.46	1.49 ± 0.70	0.79	0.70	2.03
	Multistrata	2	—	2.89 ± 0.94	—	2.23	3.55	0.69 ± 0.22	—	0.53	0.85
	Shaded Perennial	1	1477	3.16	—	—	—	0.71	—	—	—
Asia	Fallow	2	—	2.00 ± 2.52	—	0.22	3.78	0.48 ± 0.60	—	0.05	0.91
	Multistrata	11	—	4.83 ± 4.05	2.40	0.51	15.51	1.16 ± 0.97	0.58	0.12	3.72
	Shaded Perennial	2	1608 ± 188	1.79 ± 1.21	—	0.93	2.64	0.42 ± 0.18	—	0.29	0.54
	Silvopasture	1	—	0.06	—	—	—	0.01	—	—	—
Central America	Alley cropping	12	1203 ± 1000	1.88 ± 1.70	0.96	0.13	4.57	0.45 ± 0.41	0.23	0.03	1.10
	Hedgerow	1	1110	0.43	—	—	—	0.10	—	—	—
	Multistrata	1	—	3.25	—	—	—	0.78	—	—	—

Table 3. (Continued.)

Climate region	Agroforestry system	N	Tree density (# ha^{-1})	ABG biomass storage rate (tC ha^{-1} yr^{-1})				BLG biomass storage rate (tC ha^{-1} yr^{-1})			
			Mean ± SD	Mean ± SD	95% CI	Min	Max	Mean ± SD	95% CI	Min	Max
	Shaded Perennial	10	5967 ± 1724	2.28 ± 1.53	1.07	0.73	6.00	0.51 ± 0.38	0.23	0.18	1.44
South America	Fallow	2	—	4.76 ± 1.19	1.65	3.92	5.60	1.14 ± 0.29	—	0.94	1.34
	Multistrata	10	475 ± 159	2.60 ± 1.77	1.09	0.88	7.26	0.70 ± 0.41	0.25	0.28	1.74
	Shaded Perennial	2	—	2.96 ± 1.15	—	2.14	3.77	0.71 ± 0.28	—	0.51	0.90
All regions	Intercropping	12	1203 ± 1000	1.88 ± 1.70	0.96	0.13	4.57	0.45 ± 0.41	0.23	0.03	1.10
	Fallow	7	—	4.59 ± 2.77	2.06	0.22	8.46	1.10 ± 0.67	0.49	0.05	2.03
	Hedgerow	1	1110	0.43	—	—	—	0.10	—	—	—
	Multistrata	24	475 ± 159	3.67 ± 3.10	1.24	0.51	15.51	0.91 ± 0.73	0.29	0.12	3.72
	Shaded Perennial	15	4766 ± 2513	2.36 ± 1.36	0.69	0.73	6.00	0.54 ± 0.33	0.17	0.18	1.44
	Silvopasture	1	—	0.06	—	—	—	0.01	—	—	—
Tropical (*all*) (n = 288)											
	Alley cropping	90	8568 ± 8403	2.37 ± 1.45	0.30	0.13	6.58	0.55 ± 0.34	0.07	0.03	1.68
	Fallow	69	6074 ± 4529	4.42 ± 2.86	0.68	0.22	17.43	1.49 ± 1.56	0.37	0.05	10.40
	Hedgerow	3	1481 ± 463	0.47 ± 0.13	0.15	0.36	0.61	0.11 ± 0.03	0.04	0.09	0.15
	Multistrata	51	929 ± 901	3.25 ± 2.54	0.70	0.42	15.51	0.80 ± 0.60	0.16	0.10	3.72
	Parkland	7	152 ± 102	0.59 ± 0.46	0.34	0.22	1.54	0.21 ± 0.11	0.08	0.10	0.38
	Shaded Perennial	28	4236 ± 2347	2.40 ± 1.54	0.57	0.63	7.64	0.55 ± 0.36	0.13	0.15	1.76
	Silvoarable	22	880 ± 290	3.61 ± 2.87	1.20	0.64	9.71	0.89 ± 0.73	0.31	0.15	2.41
	Silvopasture	18	1609 ± 938	2.91 ± 3.94	1.82	0.06	14.05	0.79 ± 1.01	0.47	0.01	3.26

a. Based on information from the following studies: Abaker *et al* (2016), Adesina *et al* (1999), Aihou *et al* (1999), Albrecht & Kandji (2003), Beckert *et al* (2016), Brakas & Aune (2011), Bright *et al* (2017), Cardinael *et al* (2017), Chauhan *et al* (2010), Diels *et al* (2004), Dube *et al* (2012), Ehrenbergerová *et al* (2016), Fernández-Núñez *et al* (2010), Isaac *et al* (2003), Isaac *et al* (2005), Kang, (1997), Kaonga & Bayliss-Smith (2009), Kaur *et al* (2002), Kimaro *et al* (2011), Kirby & Potvin (2007), Kort & Turnock (1999), Kumar *et al* (1998), Lasco & Suson (1999), Maikhuri *et al* (2000), Makumba *et al* (2007), Mangalassery *et al* (2014), Mao *et al* (2012), Mittal & Singh (1989), Negash & Kanninen (2015), Norgrove & Hauser (2013), Nyadzi *et al* (2003), Oelbermann *et al* (2005), Palm *et al* (1999), Peichl *et al* (2006), Polzot, (2004), Rajab *et al* (2016), Rao *et al* (1991), Roshetko *et al* (2002), Schmitt-Harsh *et al* (2012), Schroth *et al* (2002), Sharrow & Ismail (2004), Siles *et al* (2010), Singh & Gill (2014), Smiley & Kroschel (2008), Somarriba *et al* (2013), Swamy & Puri (2005), Takimoto *et al* (2008), Villanueva-López *et al* (2015), Wade *et al* (2010), Wotherspoon *et al* (2014).

Mao *et al* 2012, Cardinali *et al* 2014, Sitzia *et al* 2014, Dubiez *et al* 2018, Nijmeijer *et al* 2018, Sun *et al* 2018).

The loss of SOC following a LUC can be very quick while it usually takes much longer to gain SOC (Smith 2004), especially with low tree densities. The studies using a diachronic approach to quantify SOC changes in agroforestry are rare (Beer *et al* 1990, Mazzarino *et al* 1993, Maikhuri *et al* 2000, Oelbermann *et al* 2004, Sierra and Nygren 2005, Swamy and Puri 2005, Raddad *et al* 2006, Lenka *et al* 2012, Singh and Gill 2014, Wang *et al* 2015), most of them have been performed using a synchronic or chronosequence approach. The diachronic approach has been recognized to be a more accurate method to assess SOC changes than other methods (Costa Junior *et al* 2013). More agroforestry trials using this approach should be established. LUC is often associated with a modification of soil bulk density, and a calculation of SOC stocks on an equivalent soil mass basis instead of on a fixed depth is recommended (Ellert and Bettany 1995, Ellert *et al* 2002, Wendt and Hauser 2013). Surprisingly, very few studies on SOC storage in agroforestry followed this recommendation (Bambrick *et al* 2010, Cardinael *et al* 2015a, Upson *et al* 2016, Cardinael *et al* 2017, Wiesmeier *et al* 2018).

The main difficulty to properly assess SOC changes in agroforestry systems compared to other land uses is the spatial heterogeneity. Scattered trees induce a gradient in organic inputs to the soil (Cardinael *et al* 2018), and an large number of soil samples have to be taken to explore this heterogeneity (Cardinael *et al* 2015a, Upson *et al* 2016). Developing technologies, such as visible and near-infrared spectroscopy could be used to reduce the cost and the time to monitor SOC changes (Cambou *et al* 2016, Viscarra Rossel *et al* 2016).

Deep roots and carbon storage

Roots of agroforestry trees can grow very deep in the soil due to competition with the associated crops and to soil tillage (Cardinael *et al* 2015b). Great uncertainties exist on the fate of fresh organic inputs in deep soil layers and on their interaction with older soil organic matter, such as priming effect (Fontaine *et al* 2007). However, since a large amount of root inputs can be incorporated into these systems (Germon *et al* 2016, Cardinael *et al* 2018), it would probably be very valuable to expand research on this topic. Cardinael *et al* (2018) indeed found that SOC profiles (2 m depth) in a long-term agroforestry systems where only well described if priming effect was included in the model. Only few studies have measured SOC storage in deep soil layers of agroforestry systems (Haile *et al* 2008, Howlett *et al* 2011a, Upson and Burgess 2013, Cardinael *et al* 2015a), more studies are required. Moreover, very few studies have quantified both above and belowground biomass of agroforestry systems, and the use of the root:shoot ratio determined on forest ecosystems could be problematic. Due to their low density, agroforestry trees usually grow faster than forest trees (Balandier and Dupraz 1998), and they also benefit from crop inputs (fertilization), and their root systems compete with annual crops. Moreover, agroforestry trees are often pruned. Carbon allocation between aerial and belowground parts of the trees might therefore be modified. The use of non-destructive and repeatable methods, such as ground penetrating radar could be a good way to acquire more data on agroforestry root systems (Borden *et al* 2014).

Revised stock change factors for agroforestry

Several tools use tier coefficients to provide an estimation of the C-balance associated with the adoption of improved land management options, as compared with a 'business as usual' scenario. This is for instance the case of the EX-ACT (EX-Ante Carbon-balance Tool) tool developed by the Food and Agriculture Organization of the United Nations (FAO), providing ex-ante measurements of the mitigation impact of agriculture and forestry development projects, estimating net C balance from GHG emissions and C sequestration (Bernoux *et al* 2010). EX-ACT has been developed using primarily the IPCC (2006) Guidelines for NGHGIs (IPCC 2006), complemented by other existing methodologies and reviews of default coefficients. Default estimates for mitigation options in the agriculture sector are mostly from the 4th Assessment Report of IPCC (2007) (Smith *et al* 2007).

Our newly derived factors can be used to improve these tools to estimate C sequestration in any country with a minimal amount of data by using the IPCC method. These factors may have systematic biases when not representative of management effects, climate, or soils in a particular region. Consequently, nations with available resources should consider synthesizing data from local field experiments to generate country-specific factors. However, these new estimates certainly represent a significant improvement to better account for the diversity of agroforestry systems. They were all previously included into the 'perennial crops' category, together with vineyards and orchards, and are now split into eight main types of agroforestry systems per climate and region. The presentation of emission factors for the biomass and soil using the same classification of agroforestry systems represents another important added value of this study.

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