POINT-BY-POINT REPLY TO THE REVIEWS:

RESPONSE TO REFEREE 1:

General comments

Referee: In this article the author presents an analysis of soil organic carbon stock changes associated with conversion from forest or agriculture to agroforestry. They identify significant predictor variables of SOC stock and present a large and useful data set that highlights some of the impacts of agroforestry on carbon stocks. In addition to specific comments below regarding soil texture, the nature of the precipitation that falls in this region may have significant impacts on carbon cycling. Mean annual precipitation, although a simple variable available to measure at many sites, does not always capture the underlying drivers for soil carbon cycling, see Knapp et al. (2002). Overall this manuscript presents interesting information and analysis and after addressing minor comments, is suitable for publication in SOIL.

Authors: We would like to thank the reviewer for his or her critical yet constructive comments. We have tried our best to address the issues raised and incorporate further explanations into the text to bolster and improve the manuscript.

Mean annual precipitation. While we recognize that MAP is a simple metric for soil moisture and may not fully capture the underlying drivers for SOC stocks, especially seasonal patterns, it is nevertheless a good predictor of regional scale SOC cycling. To detect some of the intra-annual / seasonal variability we examined precipitation seasonality (coefficient of variation of monthly precipitation) from the same Worldclim dataset during our data analysis. We opted not to include these results in the paper as seasonality was auto-correlated with MAP and showed similar trends: higher MAP – higher precipitation seasonality. While we do not use this seasonality data, we nevertheless have included a discussion on how precipitation seasonality (namely the monsoon), affects SOC stocks (page 11, lines 22-25):

"Both the decrease in SOC stocks and basal area at high precipitation could be explained by the torrential monsoon rains. Although the overall rainfall amount may be higher, its intensity and distribution over time causes much of it to runoff, which is then not available to plants when they need it."

Specific comments:

Referee: Experimental Design: Section 2.3: The author states that no wood is removed from the forest. Is there any history of fire in these forests? If so, is there any evidence of char or ash in the soils once they undergo conversion to agriculture/agroforestry?

Authors: Most of the studied forests are community managed forests where both wood removal and burning for the purpose of grass production is prohibited and no char or ash was found. Additionally, we did not find any char or ash in the agriculture or agroforestry systems. Unlike slash and burn practices in the humid tropics, in this region when forests are cleared for agriculture or agroforestry plantations the sites are not burnt as most of the aboveground biomass is removed and used (leaves for animal fodder or for compost material; and wood for fuelwood). To clarify the land clearing practices we have added two sentences to briefly describe this (see page 7: lines 1-2).

Referee: Results: Section 3.1: The author assumes that land use change does not affect soil texture, but there appears to be evidence to the contrary. If across plots there is a +2.3(+-0.4)% and a -5.5(+-0.5)% change in clay content with the conversion from agriculture to agroforestry, and the conversion from forest to agriculture, respectively, this appears to be a significant effect on soil texture. The author contradicts their own assumption by highlighting the importance of clay fraction as a predictor of SOC stock (Table 2). Also, changes in soil texture, particularly in clay content, can have significant impact on the soil water retention (Gupta et al 1979).

Authors: The reviewer is correct and there are indeed significant differences between the clay contents, albeit small. We attribute these differences in soil clay content to the continuous cultivation where clay particles are lost when freshly tilled soil is exposed to high intensity rainfall and are carried away in suspension in the surface runoff (Gonzalez and Laird, 2003). This explanation is found in the text page 12, line 12-15.
Considering the small differences in clay percent (2% and 5%), measurement errors may also play a role in explaining the discrepancy. The pipette sedimentation method is quite sensitive to measurement errors in the lab and values can deviate between lab technicians.

Referee: It would be helpful in this section to see the results of the t-test for the 10-30cm clay content in the appendix.

Authors: In the text we have included the p-values of the T-test, indicating that there are significant differences in clay contents. Accordingly we felt that adding the t-test results in the appendix did not add any additional information.

Referee: It is not stated clearly whether the difference in clay content occurs throughout the profile, but if the difference is within the upper 10cm it is likely that change to/from tillage, and aeolian and hydraulic erosion/deposition are all potentially significant drivers of soil texture changes and cannot be discounted. If the upper 10cm of the soil with 1600 kg m-3 bulk density and 20% clay content by mass has a change in 5% of the clay content, this results in a change of 16 Mg ha-1 of clay. If the potential for this clay to associate carbon is assumed to be 3.9% by mass (Gonzalez et al 2003) that results in a potential change of 0.480 Mg ha-1 of carbon associated with the clay fraction when these clay particles form aggregates. This amount of carbon, although below the error of 0.7-1.6Mg ha-1 associated with SOC stock changes in the upper 10cm (Figure 3), is still worth mentioning as a part of the mechanism for change in SOC stock. It is also worth noting that loss/gain of the clay fraction could contribute more significantly to the amount of carbon stored in areas of higher erosion/deposition due to its outsize role in physical and chemical stabilization of organic matter.

Authors: We agree with the reviewer. The difference in clay content in the topsoil is most likely due to tillage and subsequent erosion – especially if the soils are tilled before the monsoon. As the reviewer states, not only is the organic carbon lost directly through erosion, but the loss of soil clay particles also reduces the capacity of the soil to hold and store carbon. This mechanism has now been included in the revised text (see page 12, line 12-18).

Referee: Discussion Section 4.2 P 883 lines 17-18: The author states that erosion is of little importance. Judging from the losses in clay fraction from the soils upon land use change, this is not necessarily an aspect of land use change that can be overlooked at all sites. Dourte etal (2012) reports rainfall rates for Andhra Pradesh and has made calculations showing that high rates of runoff are possible. Using Dourte's data for monsoonal rainfall intensity as a proxy for nearby areas, of similar rainfall quantity, runoff, and therefore erosion of surface fines and associated fine-grained surface organic matter cannot be dismissed, especially for the agricultural sites without the protection of a closed canopy for diffusion of the rainfall energy. Including this in the discussion would also help make this data more interpretable in areas where steeper slopes and high rainfall energies are present.

Authors: Erosion is no doubt an important way in which carbon and clay particles are lost. Accordingly we have removed the phrase where we state that "soil erosion is of minor importance". Considering that all our plots were located on flat or gentle slopes and that we only did a one-time sampling we could not quantify the magnitude on SOC and clay losses from erosion. Instead we have bolstered this section by citing the findings from Dourte et al. (2012) and Gonzalez and Laird (2003) (see page 12, line 12-18).

Technical Corrections

Referee: P872 line 4: remove "however"

Authors: corrected

Referee: P 874 Line 16: “stocks” should be “stocks”’ or “: : :and changes to SOC stocks along a forest: : :”

Authors: corrected

Referee: P880 line 19 “: : :soil SOC: : :” should be “SOC”

Authors: corrected

Referee: P876 lines 8-9 “cinnamom” should be “cinnamon”

Authors: corrected

Reference list:

Dourte, D., Shukla, S., Singh, P. and Haman, D.: Rainfall intensity-duration frequency relationships for Andhra Pradesh, India: changing rainfall patterns and implications for runoff and groundwater recharge, Journal of Hydrologic Engineering, 18(3), 324-330, 2012.

Gonzalez, J. M. and Laird, D. A.: Carbon Sequestration in Clay Mineral Fractions from C-Labeled Plant Residues. Soil Science Society of America Journal, 67(6), 1715-1720, 2003.

RESPONSE TO REFEREE 2:

General comments

Referee: This study reports an interesting and unique data set on land use and management changes from forest to agriculture to agro-forestry systems in India. There are few studies on soil carbon (SOC) dynamics after land use transitions from India and also few studies from agro-forestry systems (AFS), covering different AFSs making the study very valuable. The study is written and structured very clear and professional. However, there is one major concern that needs to be considered in order to get this paper in a publishable status. Also some minor remarks maybe considered to improve the paper.

Authors: We would like to thank the reviewer for his or her thorough evaluation of the manuscript. As a result we have made numerous changes in the manuscript to address the issues he/she has raised.

Major remark

Authors: The response for this major remark will be addressed in three parts.

Referee: The depth distribution of SOC stock changes is a critical issue (Fig. 3) since you found minor differences in relative and absolute SOC stocks changes throughout the soil profile. This aspect required more explanations (p. 9, l. 25 f) and more attention.

Authors: We would argue that differences were not minor. Doubling of soil carbon is not minor.

Within a time period of several decades land use changes should generally affect top soils more than subsoils since most carbon input occurs close to the soil surface from litter and roots. Poeplau and Don, 2013 Geoderma, e.g., found only 10% of the SOC stocks changes in 30-80 cm depth, also for afforestation with similar age and likely also similar rooting distribution as in AFSs. About 90% of the changes occurred in the topsoil (0-30 cm depth). This is also reported in many other studies (e.g. Degryze et al. 2004, GCB) on land use change effects.

Authors: We think the reviewers may have misinterpreted the meaning of the depth profile figure (Figure 3). This depth profile shows the percentage change in soil carbon for each respective depth and not in relation to the full soil profile. For instance, if there is a 100% increase at 60-100cm it simply means that at that depth the SOC stock doubled.

Nevertheless, the reviewer is partly correct in that the changes are most intense at the soil surface. This is evident if we look at the magnitude of SOC stock changes normalized for 10cm increments throughout the soil profile (see grey bar in Fig. 1). This shows that between 17-32% of the soil profile SOC changes took place in the top 10 cm. However, when we consider the whole soil profile (which has a much bigger volume), there are very large carbon gains below 30cm. In homegardens 58% of the gains occurred below 30cm, for coffee 26%, for coconut 59%, and for mango 50%.
In Fig. 3, we have now added the corresponding carbon change in percent of the overall change in the soil profile. We opted not to show the normalized values (as in Figure 1) as we thought it would confuse the reader. In the text, we have provided more detail on where in the soil profile the SOC changes are occurring in terms of the overall change (see page 9, line 17-18).

In contrast to the papers the reviewer cites, which are all in the temperate zones, we found a few a papers in the tropics which showed similar trends as ours (Saha et al, 2010; Hooker and Compton, 2003). Most notably is the paper by Saha et al 2010, who also investigated soil carbon in Indian AFS (coconut, homegardens, and rubber). In comparison to upland rainfed rice paddy fields (not flooded) most carbon differences in the AFS were in the subsoil (here below 20cm). For coconut there was only a 3% gain in at the soil surface and for the homegarden (HGL and HGS) only 7% combined (interpreted from Fig. 2 and values shown in the Table beside it).

We believe the carbon gains at depth are a result of a number of processes:
1. The deep rooting profile of the AFSs means that organic matter inputs are injected into the subsoil. Coconut trees, for instance, have very fibrous and profuse root systems. This is in clear contrast to agriculture where annual crops have shallow rooting systems and are tilled frequently.
2. The high intensity precipitation (monsoon rains) in the humid and sub-humid regions leads to higher water infiltration and result in a high mobilization of DOC (Rumpel and Kögel-Knabner, 2011; Follett, et al., 2009).
3. Collection of coconut leaves for domestic use (thatching, cooking) means there is little organic matter input at the soil surface – for this AFS.
4. Time. Most of these AFS are quite old (ranging in age from 45 to 85 years) and accordingly there has been sufficient time for SOC stocks to accumulate at depth.

The simplest explanation of uniform SOC differences throughout the soil profile are differences in the soil type or soil texture that put the soils to different SOC levels. Thus, differences between land use systems may thus be a result of soil intrinsic variables and can thus not be attributed to land use. If the assumption that the small systematic differences in clay content between the paired sited had no effect on the results (Chapter 3.1) should be checked using SOC loads per %clay from the literature (e.g. Leifeld and Kogel-Knabner, 2005, Geoderma) or using the own model that contains clay a predictor variable (see also comment of referee #1 on this contradiction that need to be solved). Further work is required to disentangle clay content effects from land use effects.

Authors: On the reviewer's advice we explored the implication the clay differences have on SOC stocks. Specifically, we calculated a SOC correction factor that would remove the effects of the clay differences – on the assumption there was really an intrinsic difference in the soils. The correction factor was calculated using the relationship clay has with soil organic carbon (at each individual depth, in undisturbed systems) and then this correction constant was added to the SOC stock at the converted land-uses (agriculture or AFS). For instance, for agriculture where there was on average 5.5% less clay than the forest, we recalculated the new SOC stock of the agriculture by adding the theoretical amount of C stored that would have been stored by higher clay content. For the AFS systems there was 3.2% less clay than the forest (an increase of 2.2% from the agriculture). Accordingly, to correct for the clay difference, the carbon contents increased in these converted systems (compare red and black dots in Fig. 3).

If we look at the changes in the depth profile for the conversion of agriculture to AFS we observe a decrease in the percentage change (compare red and greyscale dots in the Figure below) – as the reviewer had hinted at. This change however simply reflects that there was a larger correction factor made to the agriculture (5.5% clay difference) than to the AFS systems (3.2% clay difference).

Basically, this clay correction exercise has shown that the story of the paper does not change. It simply shifts the absolute SOC stocks of both agriculture and AFS slightly higher (Fig. 3). While there may appear to be big decreases in the relative changes (Fig. 4), this simply reflects that SOC in the agriculture increased more (higher clay correction factor; 5.5% diff. in clay) than the AFS (lower clay correction factor; 2.3% diff. in clay).

Ultimately **however we do not believe that there was an intrinsic difference between the soils of the plot pairs**. During the fieldwork we implemented rigorous site selection criteria to find comparable plot-pairs within each cluster. Our site selection criteria included:

- Soil texture: (perhaps most importantly) we compared soil textures at different depths (well into the sub-soil) of prospective sites using the feel test. First, we used an auger to collect soil samples from prospective sites and later once the soil samples were collected, we carefully compared soil textures and based on texture differences either accepted or rejected sites for this study. While the feel test method may not yield quantitative values of grain sizes, it is more than sufficient to compare whether soils are similar or not.
- Distance between plot pairs: we looked for sites located in close proximity of another, with all of the plots within a cluster located within a maximum of 1-km

distance of each other. Keeping the plots as close as possible should minimize pedological differences in the soil types.

- Topography: we chose sites on similar landscape positions with similar slopes. This was not difficult however since most of the sampling region has only light undulating hills with homogeneous soils. This is reflected in the plot slopes which were on average 3% and maximally 7% (measured with a clinometer).

In contrast to other regions of the world where remnant intact forests are difficult to find and are generally located on poor agriculture soils, the forest we used in this study were originally selected because of their religious significance. These so-called “sacred groves” were almost always located centrally, surrounded by agriculture and agroforestry systems.

As we already explained above (reviewer #1), we believe that the (small) clay differences are a result of erosional processes taking place at the soil surface over a period of decades. This has also been observed in other studies (Gonzalez and Laird, 2003). The loss of clay particles through erosion losses has now been included in the text (see page 12, lines 12-18) as a potential mechanism for the carbon loses.

Minor remarks

Referee: 1. Is there any renewing of AFS? For mango, e.g., it was reported that farmers use the establishment phase differently that the later stages of the plantation (p. 5, l. 15). Is AFS permanent? Is it reconverted to cropland or are trees cut at some time as part of a AFSs renovation process which possibly would effects SOC?

Authors: The AFS are permanent. Nevertheless, there is a constant renewal of trees within the AFS but only insofar that dead and diseased trees are removed and replaced with young trees. Considering that this is a gradual process taking place over the duration of the AFS lifespan, there should not be any abrupt effects on SOC.

Referee: 2. Provide the diameter of the probe (p. 6, l. 2) and the number of replicates of bulk density sampling (p. 6, l.5).

Authors: The core was 5.3 cm in diameter and 7.5 cm in height, which equals 165 cm^3. Two replications samples were taken at each measurement depth. This information was added to the text (page 7, line 13-16).

Referee: 3. Mention if any carbonate/inorganic carbon was present in the soils or if soil carbon is equal to soil organic carbon in this study.

Authors: There were no carbonates in the soils in our study region. All the plots were located on the Indian Shield which consists of rocks formed during the Precambrian (Archean and

Proterozoic Eons). These rocks consist of gneisses, charnockites (high grade metamorphic rocks) and granites and are all devoid of carbonates. We added this in the text (page 7, line 18-20).

Referee: 4. What is difference between mass correction (after Ellert and Bettany 1995) and the method you applied with using the forest bulk density for all treatments? (p. 6, l. 12 f). For cropland conversion to AFS the land use system with the lowest bulk density (either cropland or AFS) should be used for a mass correction, not the bulk density of the forest that is not part of this comparison.

Authors: The discussion of how to deal with bulk density changes caused by land-use change in the SOC calculation has featured in numerous papers (for example: de Blécourt et al. 2013; de Koning et al 2003; Mekuria et al. 2011; Powers et al. 2011; Veldkamp 1994). Changes in bulk density (caused by land-use change) can have a profound influence on SOC stock comparisons and accordingly needs to be addressed to achieve accurate estimates. The approach we use here (using bulk density estimates from the forest reference plot) is a method introduced by Veldkamp (1994) and has been widely used. **Essentially, Veldkamp (1994) determined that it is the same whether one uses the bulk density of the reference land use or uses fixed soil mass by adjusting the soil depth in the converted land use.**

We used the bulk density of the forest reference to standardize all our SOC stock calculations to the same reference. With this approach our change estimations from agriculture to AFS will be on the conservative side. Had we used the bulk density of the agriculture for our AFS SOC calculations, our stocks would have been substantially higher and accordingly also the gains. Lastly, the measured bulk densities of the AFSs (1.08±0.01 g cm^{-3}) were just slightly higher than the forest (1.06±0.01 g cm^{-3}) reference.

Referee: 5. Chapter 3.1 should become part of the material and methods section in order to start the results section not with methodological assumptions.

Authors: On the reviewer's advice, we have now incorporated this information into material and methods section. In moving it we have tried to maintain the same message. (page 5, line 8 to 19).

Referee: 6. P. 8 l. 13ff: Did you include any variable for the litter input in the analysis? You mentioned that at some AFS litter was extracted at some not. I propose to estimate whether liter extraction had an effect on SOC stocks in the regression analysis directly by using an estimate for the litter input (not only via basal area) – if available.

Authors: Unfortunately, we could not measure nor could we find any data on litter inputs into these different systems. There is simply too little research done on this in this region.

Referee: 7. Please provide a reference that aluminum toxicity plays a role also for pH 4.5, which was the lowest pH in your study. I assume that you need lower pH for toxic effects of aluminum.

Authors: The reviewer is correct. Aluminum toxicity starts at a pH of approximately 5. Accordingly, we have removed aluminum toxicity as a possible explanation. We have now generalized this explanation to reflect that decomposition processes at either end of the pH scale (acidic or basic) are retarded when the biochemical environment is sub-optimal (page 11, line 8-13).

Referee: 8. P. 10. L. 5: How does mineralogy affect SOC at high pH? Rephrase this sentence in order to mention the process/mineral to which this affect is attributed.

Authors: In our original manuscript the justification for the higher SOC stocks at higher pHs was based on the explanation given by van Noordwijk et al. (1997). In his study he observed a similar relationship and attributed the phenomenon to clay minerology. However, on closer inspection of the paper we discovered that they do not provide any evidence - or even a citation - as to how they reached this conclusion. We have now rewritten this section to reflect that decomposition processes at either end of the pH scale (acidic or basic) are retarded when the biochemical environment is sub-optimal (page 11, line 8-13).

Referee: 9. P. 10. L. 30: How does clay mineralogy affect SOC changes? Rephrase this sentence in order to mention in which way clay mineralogy affect SOC changes according to Powers et al..

Authors: We have rephrased this sentence.

Referee: Fig 2 and 3: Indicate significant differences with different letters.

Authors: We added the letters for Figure 2, but not for Figure 3. We opted not to include them for Figure 3 because we felt it was not a legitimate comparison to examine the relative SOC changes (in percent) between AFS types, as this does not reflect the actual magnitude of change.

Referee: Fig 2: Explain in figure caption if you display absolute or relative changes. The arrows are not clear, since they are not clear enough connected to either humid or dry subhumid data. Two separate arrows are maybe better or no one.

Authors: The graphs show the absolute SOC stocks – not changes. We have changed the figure caption to make this clear. We have also removed the arrows and the associated numbers because it was not clear what they meant.

Reference list:

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Veldkamp, E.: Organic carbon turnover in three tropical soils under pasture after deforestation, Soil Sci. Soc. Am. J., 58(1), 175–180, 1994.

On the rebound: soil organic carbon stocks can bounce back to near forest levels when agroforests replace agriculture in southern India

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Abstract

Tropical agroforestry has an enormous potential to sequester carbon while simultaneously producing agricultural yields and tree products. The amount of soil organic carbon (SOC) sequestered is ~~however~~ influenced by the type of the agroforestry system established, the soil and climatic conditions and management. In this regional scale study, we utilized a chronosequence approach to investigate how SOC stocks changed when the original forests are converted to agriculture, and then subsequently to four different agroforestry systems (AFSs): homegarden, coffee, coconut and mango. In total we established 224 plots in 56 plot clusters across four climate zones in southern India. Each plot cluster consisted of four plots: a natural forest reference plot, an agriculture reference and two of the same AFS types of two ages (30-60 years and >60 years). The conversion of forest to agriculture resulted in a large loss the original SOC stock (50-61%) in the top meter of soil depending on the climate zone. The establishment of homegarden and coffee AFSs on agriculture land caused SOC stocks to rebound to near forest levels, while in mango and coconut AFSs the SOC stock increased only slightly above the agriculture stock. The most important variable regulating SOC stocks and its changes was tree basal area, possibly indicative of organic matter inputs. Furthermore, climatic variables such as temperature and precipitation, and soil variables such as clay fraction and soil pH were likewise all important regulators of SOC and SOC stock changes. Lastly, we found a strong correlation between tree species diversity in homegarden and coffee AFSs and SOC stocks, highlighting possibilities to increase carbon stocks by proper tree species assemblies.

Key words: land-use change, carbon sequestration, homegarden, coffee, coconut, mango

1 Introduction

Land-use changes in the tropics are responsible for approximately 10% of the human induced greenhouse gas emissions and are expected to remain the second largest source of carbon (C) emissions in the near future (Achard et al., 2014). Considering that tropical forest soils store a similar amount of organic carbon (692 Gt in the top 3-m; Jobbágy and Jackson, 2000) as the atmosphere (589 Gt C; Ciais, et al., 2013), and that tropical climates foster rapid organic matter decomposition, land-use changes can result in strong carbon fluxes into or out of the soil. The conversion of tropical forests to agriculture causes both a release of stored soil organic carbon, often in the form of carbon dioxide, but it also results in a decline in soil productivity. To reduce carbon emissions from agriculture while simultaneously maintaining agricultural productivity it is necessary to identify and implement simple and cost effective measures to store and capture carbon. In this context agroforestry practices, which integrate trees into agricultural systems, offer a unique opportunity to sequester atmospheric carbon while also growing food, diversifying incomes (e.g. from sale of wood, fruit and staple foods), and simultaneously providing numerous environmental benefits. These include mitigating soil erosion (Montagnini and Nair, 2004), improving soil structure (Lal, 2007), pumping up nutrients from the subsoil (Das and Chaturvedi, 2008) and sequestering atmospheric carbon (Lal, 2007; Nair et al., 2009). Agroforestry systems (AFSs) have higher SOC sequestration rates than conventional agricultural systems (Nair et al., 2009) as the trees they have comparatively higher litter inputs and are capable of inserting carbon deep in the soil with their root systems (Montagnini and Nair, 2004).

Furthermore, tree species diversity in AFSs can have a large impact on organic matter turnover as diverse species mixtures can add different qualities of organic matter which correspondingly influence soil microbial communities and decomposition processes (Six et al., 2002; Acker et al., 2002). Niche differentiation and resource partitioning may lead to a better use of space and nutrient uptake and thus increase ecosystem carbon inputs (Thakur., et al., 2015) . Although it is recognized that AFSs have many benefits, their C sequestration potential, especially belowground, remains largely unexplored (Montagnini and Nair, 2004). Concentration and SOC turnover rates in AFSs vary significantly with biophysical site properties such as climate (Liu et al., 2011), vegetation, land-use types (Cadotte, 2013; Saha et al., 2010), soil type and texture (Six et al., 2002; Chaplot et al., 2010), land management (Hevia et al., 2003) and their interactions (Powers and Schlesinger, 2002). It is generally recognized that temperature and precipitation are the most important variables regulating SOC (Chaplot et al., 2010; Liu et al., 2011). Since both affect the type of vegetation cover, the quantity of biomass production and the rate of SOM turnover (Hevia et al., 2003).

It is estimated that there are approximately 25.3 million hectares (Dhyani et al., 2013) of AFSs established across India, whereby the type of AFS established depends on the biophysical site conditions and the socioeconomic status of the owners. Despite this, regional-scale studies evaluating the impacts the establishment these land-use types have on SOC stocks remain relatively scarce (Albrecht and Kandji, 2003; Mutuo et al., 2005, Saha et al., 2010). Here in this study, we quantified SOC changes associated with the conversion of forest to agriculture and subsequently from agriculture to four different AFS types (homegarden, coffee, coconut and mango). Our plots were established across southern India in a broad range of biophysical conditions, ranging from semi-arid to humid climates and in soils with low and high activity clays. The objectives of this study were as follows:

(i) to quantify SOC stocks and ~~SOC stocks~~ changes to SOC stocks along a forest – agriculture – AFS trajectory, and

(ii) to determine the biophysical drivers regulating SOC stocks and its changes.

2 Materials and methods

2.1 Study area

The study was conducted across three states in Southern India (Kerala, Karnataka and Andhra Pradesh; Fig. 1), in an area that has a long-standing history of diverse agroforestry-based land-use practices. The region has a tropical monsoon climate, with a rainy season from May to October and a distinct dry season from November to April. The mean annual precipitation (MAP) ranges from 627 to 3422 mm and mean annual temperature (MAT) ranges between 21.9°C in the highlands to 27.2°C at lower elevations (Hijmans et al., 2005). The soils were classified as Luvisols, Acrisols or Nitisols.

2.2 Sampling design and site selection

In this study we investigated how SOC stocks changed when forests are converted to agriculture and subsequently to agroforestry systems in four different climatic zones along a precipitation gradient (humid, moist sub-humid, dry sub-humid and semi-arid; based on classification by ICAR (1984)). Each AFS type was sampled in two of four climatic zones based on its relative importance in terms of area, production and income in the region (Table 1). Using a chronosequence approach we established 56 plot clusters (Fig. 1). A plot cluster consisted of four land-use types: a natural forest reference and an agriculture reference and two AFS plots at different ages, medium (30-60 years) and old (>60 years). Seven plot clusters were established for each AFS type in two climatic zones. In total 224 plots were set up (4 AFSs x 2 climate zones x 7 clusters x 4 land-use types).

The plot clusters were always centered around the natural forest reference plot and located within a maximum distance of 1-km of each other. To reduce edge effects, the forest plots were selected at least 40 m from the forest edge. ~~Clusters~~ Plot pairs (either forest with agriculture or agriculture with AFS) were carefully selected to ensure soil and climate conditions were ~~chosen to only include plots with~~ similar ~~biophysical conditions~~: 1. All plots were located on similar landscape positions on flat to gently sloping terrain (average: 3%; maximum: 7%). 2. Using a feel test we compared the subsoil texture of all possible candidate sites and chose only those with comparable soil textures. An *a posteriori* texture analysis revealed that there were small differences in surface clay percent at 10-30 cm. For the ~~(e.g. soil texture, landscape position, elevation, slope).~~ forest to agriculture comparison, the clay content difference was -5.5±0.5% (P>0.05), and for the agriculture to AFS the difference was 2.3±0.4% (P>0.05). 3. ~~Furthermore we chose~~ Selected sites ~~which~~ were all well drained, had deeply weathered soils (no stones) and had not been limed.

2.3 Land-use systems and forest reference

Each AFS type consisted of a unique combination of trees and crops (Table 1) and originated from former agricultural land with the exception of 19 coffee plots and one homegarden plot which replaced forests directly. Pictures of the investigated land-use types in the different climate zones are found in Fig. A1 in Appendix A.

The homegarden AFS has a multilayered canopy, consisting of a diverse tree-admixture of different ages and sizes. The multipurpose trees grown here are found in association with shrubs and herbaceous species (Kumar et al., 1994). The majority of households in the humid and moist sub-humid climate zones manage homegarden AFS to (partially) satisfy their fruits, spice and vegetable needs (such as cassava, banana and ginger). For management, farmers loosen the soil once a year during vegetable cultivation (Appendix A, Figure A1).

Coffee AFSs are mainly grown in the humid and moist sub-humid region of the Western Ghats. Coffee is grown in the understory of both native shade tree species and planted trees and is often inter-cropped with spices such as pepper, cardamom, cinnamon~~m~~, clove and nutmeg (Appendix A, Figure A1). Litterfall from shade trees and pruning products mean that this system receives substantial organic matter inputs. The soils in coffee AFS are typically hand tilled once every two to three years.

Coconut is primarily grown by smallholder farmers in southern India. The four southern states Karnataka, Andhra Pradesh, Tamil Nadu and Kerala together produce 92% of India's total coconut production. In the humid region of Kerala state, coconut is extensively grown with vegetables, whereas in the dry sub-humid region it is grown together with food grains (such as maize, turmeric and finger millet) (Appendix A, Figure A1). These crops are cultivated at different stages of coconut plantation development depending on the amount of incoming light. Since most of the coconut plant parts (leaves, stems) are useful to the farmers for various household uses, little organic matter is left onsite. In dry sub-humid zone, farmers plough the land two to three times a year for agriculture crop production.

Mango is an important commercial fruit crop in India which ranks first among world's mango producing countries, accounting for about 40% of the world production (Sekhar et al., 2013). In Karnataka and Andhra Pradesh states, mango is predominantly grown in drier climate (dry sub-humid and semi-arid) and is predominately cultivated by smallholder farmers. Many farmers adopt wide row spacing and grow agriculture crops between the rows (Appendix A, Figure A1). Since it normally takes 12-15 years to establish a closed canopy, farmers utilize this duration to cultivate agriculture crops, such as finger millet and maize. In later stages, those crops are no longer profitable and farmers switch to grow fodder and short rotation crops for the household consumption.

Agriculture under humid and moist sub-humid climate zones is only practiced by smallholder farmers. Here, staple foods like tubers and vegetables for subsistence use are grown, with only organic matter inputs as nutrient supplement sources (Appendix A, Figure A1). In the dry sub-humid and semi-arid climate zones commercial agriculture crops are grown with a high input of both fertilizers and pesticides. All agricultural fields are typically ploughed two to four times a year, often with a small tractor. During agriculture establishment the forests were cleared using hand tools and most above-ground biomass was removed for domestic use. Sites were not burnt.

The forest plots of our study were most often community managed and considered "sacred groves". Due to religious reasons people do not remove any wood from there. The remaining forests which we sampled were government owned; these too were relatively undisturbed. All forests were located in or within the vicinity of the village and were highly protected. Evergreen forests were found in humid climate, moist deciduous forest in moist sub-humid climate zone, dry deciduous forest in dry sub-humid and scrub forest in semi-arid climate (Appendix A, Figure A1).

2.4 Sampling and lab analyses

In each 20 x 20m plot we took soil samples using a soil auger~~,~~ from 12 fixed locations around the plot at predefined soil depths (0-10, 10-30, 30-60 and 60-100 cm). The samples for each respective depth were pooled and thoroughly mixed. A ~~small~~ soil pit (1 x 1 x 1 m) was dug in the center of the plot ~~where~~ for ~~soil cores were taken for~~ soil bulk density determination by embedding a cylindrical core (165 cm^3, diameter of 5.3 cm, height of 7.5 cm) at 5, 20, 45 and 80 cm depths and replicated twice per depth.~~,~~

Total soil carbon and nitrogen concentrations were analyzed using a C~~:~~N Elemental Analyser (Vario EL III, Elementar, Hanau, Germany). As the entire region is underlain by high grade metamorphic rocks and granites of the Indian Shield no carbonates were expected in these soils and no attempts were made to remove them. The soil carbon stock (Mg C ha^{-1}) was calculated by multiplying the carbon concentration (g kg^{-1} of soil) with bulk densities of the respective depth interval (kg m^{-3}) and the layer thickness (m) and up-scaled to one hectare. Total soil carbon stocks for the top meter of soil were calculated as the sum of all depth intervals. To ensure comparability of plot pairs and to avoid overestimation of SOC stock changes we used the bulk density data of the respective forest plots to calculate the soil carbon stock of the agroforestry and agriculture plots within each the cluster (Veldkamp et al., 1994). Additionally, we determined the pH of air-dried soil in a 1:2.5 soil-to-water solution for all sampling depths, and soil texture for two depths (0-10, 10-30 cm) using the pipette sedimentation method.

At each plot, we measured tree basal area for all trees with a diameter at breast height greater than 10 cm. These tree species were identified to the species level. Furthermore, we recorded information on slope, elevation and geographical coordinates of each plot. Through informal interviews with the land-owners we got information on current and past land-uses and their management practices. Meteorological data such as mean annual temperature and mean annual precipitation for the selected plots was retrieved from the WorldClim database (Hijmans et al., 2005).

2.5 Statistical analysis

To verify that plots were satisfactorily selected in the field and that the soils of the plot pairs were inherently similar we did an *a posteriori* comparison of soil clay percentages in the subsoil (10-30 cm) of the plot pairs using a paired t-test analysis. To estimate the size of SOC stock changes following land-use change (either from forest to agriculture or from agriculture to AFS), we calculated the difference in SOC stocks between plot pairs. The percent-difference in SOC stocks was then expressed as the relative change to the respective reference SOC stock (forest reference for agriculture; agriculture reference for AFSs) (Relative change = ($SOC_{converted} - SOC_{reference}$) / $SOC_{reference} \times 100$). The influence of climate and site variables on SOC stocks and relative SOC stock changes was evaluated by linear and non-linear regression analyses across AFSs for single variables and with stepwise linear multivariate analyses for each system.

The residuals of all models were checked for normality with QQ-plots; models were considered significant at the $Pp \geq 0.05$ level. All statistical analyses were done using the software package R - version 2.15.0 (R Development Core Team, 2014).

3 Results

~~3.1 Comparability of plot pairs~~

~~Based on the assumption that land-use changes do not directly affect soil texture, we found that the clay percent changes for the forest-to-agriculture conversion in agricultural plots were slightly lower than in the forest reference (difference of -5.5 ± 0.5%), while for the agriculture-to-AFSs conversion, clay percentages were slightly higher in the AFSs (difference~~

of 2.3 ± 0.4%). Considering how small these differences are, we feel confident to attribute any differences in SOC stocks to land-use changes.

3.23.1 Land-use change impacts on SOC stocks

Among the land-use types investigated, SOC concentrations (data not shown) and SOC stocks were highest in natural forest, lowest in agriculture and intermediate for the different AFSs (Fig. 2). Deforestation for agriculture resulted in a strong decrease in SOC stocks across all climate zones, creating a loss of 50% to 61% of the original SOC stock. The resulting SOC stocks of AFSs however were dependent on AFS type. While SOC stocks in homegarden and coffee AFSs rebounded to near forest levels, the SOC stocks in both coconut and mango AFSs increased only marginally compared to the agricultural reference (Fig. 2 and 3).

Of the AFSs studied, SOC stocks in the top meter of soil were highest in coffee (156±10 Mg C ha^{-1}) followed by homegarden (151±5 Mg C ha^{-1}), coconut (98±7 Mg C ha^{-1}) and lowest in mango AFSs (76±3 Mg C ha^{-1}). AFS establishment on agricultural land caused SOC stocks to increase significantly in all AFSs, with SOC gains ranging from ~45% in coconut in dry sub-humid zones to ~103% in homegarden in humid zones (Fig. 3). Furthermore, significant SOC stock gains were measured at all soil depths (with the exception of coffee in the subsoil (at 60-100 cm)). Homegardens exhibited the highest overall SOC stock gains, with relative changes within each depth layer being relatively uniform throughout the soil profile. This was followed by coffee, which, in contrast, had highest SOC stock gains at the soil surface and decreased with depth. Lastly, SOC stock gains in mango and coconut AFSs were comparatively low, but constant throughout the soil profile (Fig. -3). When expressed in terms of overall changes throughout the whole soil profile, most SOC gains were concentrated at the soil surface (see grey bar in Fig. 3). Nevertheless, when considering the whole soil profile (which has a much bigger volume), there are large SOC gains below 30 cm. For homegardens, 58% of the gains occurred below 30 cm, for coffee 26%, for coconut 59%, and for mango 50%.

The climate zone had a marginal influence on overall SOC stocks of a given AFS where only coconut and mango AFSs showed a tendency towards higher SOC stocks in the respective wetter climate zone (Fig. 2). Also the SOC stocks of the AFSs did not differ among the two age categories sampled (Fig. 2).

~~3.3~~3.2 Predicting SOC stocks and relative changes in SOC stocks

In undisturbed forest ecosystems 82% of the variance in SOC stocks could be significantly explained by five variables (MAP, MAT, basal area, clay fraction and soil pH) using stepwise multivariate regression analyses (Table 2). While tree basal area and clay fraction exhibited positive linear correlations with SOC stock, both soil pH and MAP exhibited parabolic and inverse parabolic relationships respectively (Fig. 4a-d). For pH, SOC stocks were lowest at a near-neutral conditions, while SOC stocks peaked between 2000 and 3000 mm yr^{-1} MAP.

Basal area was the single best predictor of forest SOC stocks. This is evident in both, the scatterplot graphs in Fig. 4b and from its dominant position in the multivariate regressions for all land uses investigated (Table 2), except in agriculture which had no trees. Likewise, soil clay fraction was also an important predictor of ~~soil~~ SOC and was present in all AFSs regression equations except homegardens. Although MAT was an influential predictor of forest SOC stocks in the stepwise regression (found in 3 of the 6 prediction models; Table 2), yet taken as single predictor its influence on SOC stocks remains insignificant. SOC stocks in both homegarden and coffee AFSs are further positively correlated to the Shannon Wiener species diversity index of trees (Fig. 5). Coconut and mango AFSs however were not included as they are monocultures in terms of tree or palm species admixture.

The SOC stock losses attributed to the conversion of forests to agriculture could be predicted by two variables: clay fraction and MAT (Table 2). Thereafter, when agriculture plots were converted to AFSs, SOC stock changes could be predicted by MAP, MAT, basal area, clay fraction and soil pH in varying importance for the individual AFSs and for all AFSs combined (Table 2). While MAP, basal area, and clay fraction all exhibited positive linear correlations with SOC stock change, soil pH exhibited a parabolic relationship with SOC change. For the latter, SOC stock losses were highest in acidic soils, lowest near neutral pH, and again higher in slightly alkaline soils (Fig. 4e-h).

4 Discussion

4.1 SOC stocks in natural forests

The SOC stock is a balance of incoming carbon from organic matter and carbon losses either through decomposition processes or dissolved organic carbon (DOC) leaching (Davidson and

Janssens, 2006; Raich et al., 2006). Both the carbon inputs and outputs however are strongly affected by ecosystem productivity, vegetation type, climate, clay mineralogy, soil pH, nutrient availability, soil aggregates and texture (Lal, 2004; Six et al., 2002; Chaplot et al., 2010; Don et al., 2011).

Although we did not measure organic matter inputs directly, we found a very strong correlation between SOC stocks and plot basal area, which could be indicative of organic matter litter inputs (Fig. 4b; Lebret et al., 2001). Once organic matter enters the soil, the soil's physical characteristics and biochemical environment plays an important role in how SOC is either stabilized, mineralized or leached (Raich and Schlesinger, 1992; Six et al., 2002; Zinn et al., 2007a). The ~~C~~clay mineralogy and soil clay fractions ~~can~~ play a critical role in how much SOC can be stored by the soil, its residence times and its susceptibility to land-use change ~~affect total SOC stocks, carbon residence times and susceptibility of the soil C pool to land-use change~~ (Zinn et al., 2007b). ~~-~~Clays can stabilize organic matter particles through clay-humus ~~through mechanisms such as differential chemical~~ complexation, or ~~,~~ ~~aggregation or~~ physically protect ~~ion~~ organic matter molecules from further mineralization by trapping them in clay macroaggregates ~~from decomposers~~ (Sollins et al., 1996~~; Six et al., 2004~~). ~~Furthermore, soils with higher clay fractions have lower decomposition rates and can store carbon for longer periods than soils with coarser soil fractions (Six et. al., 2002). This~~ The ~~is highlighted in our study where we observed a~~ strong positive correlation between SOC stocks and clay fraction we measured reflect the importance of these processes on SOC storage (Table 2, Fig. 4c). Next, the parabolic relationship we observed between soil pH and forest SOC stocks (Fig. 4d) reflect how the soil biochemical environment is critically important for soil microbial communities that decompose organic matter ~~(~~ (Motavalli et al., 1995). The higher SOC stocks found in the acidic and basic soils in this study ~~The high SOC stocks which we found under acidic conditions indicate~~ indicates that the unfavorable biochemical environment retards microbial communities that ~~that~~ decompose the organic matter~~ition processes declined, perhaps due to the accumulation of toxic cations such as aluminum which hindered microbial populations~~ . At a near-neutral soil pH, conditions were ideal for microbial communities and accordingly decomposition rates were high, resulting in little SOC accumulation. ~~Finally, at a pH of above seven the SOC stocks were again slightly higher and such trends have previously been attributed to differences in soil mineralogy (van Noordwijk et al., 1997).~~

As expected, regions of higher rainfall stored more SOC than drier zones (Fig. 2). This is likely because the natural forests in the humid zone have higher net primary production given the favorable year-round water availability compared to forests in the drier regions. Unexpectedly however, at very high levels of precipitation (>3000 mm y^{-1}) SOC stocks declined again (Fig. 4a). We suspect that this decrease at high precipitation is related to the corresponding lower ecosystem biomass (using basal area as a proxy; Fig. A2, Appendix A). Both the decrease in SOC stocks and basal area at high precipitation could be explained by the torrential monsoon rains. Although the overall rainfall amount may be higher, its intensity and distribution over time causes much of it to runoff, which is then not available to plants when they need it. Meanwhile, it has been reported that the leachate from these soils may also contain high DOC concentrations (Lal, 2003).

Although MAT is a significant predictor of forest SOC stocks, its influence can only be evaluated in interaction with other variables (Fig. A3a, Appendix A). Although one would expect a strong correlation between MAT and MAP, it was not present here. While MAT is mainly driven by altitude, MAP depends on more complex weather phenomena that differ among climate zones. This might also explain why there is no clear relationship between MAT and SOC when other variables are not included in the analysis.

4.2 Agriculture establishment causes up to 61% SOC losses

In comparison to a large pool of studies on this land-use conversion conducted in the tropics, the SOC losses detected here for the different climate zones were at the higher end (50-61%). Results from two meta-analyses report SOC stock decreases on average between 18% (Powers et al., 2011) and 25% (Don et al., 2011) for this land-use conversion in the tropics. Powers et al. (2011) however report that large SOC losses are possible (to a maximum of 76%), but the losses depend on the clay mineralogy and precipitation regimes. Nevertheless, in our study we measured significant decreases in SOC stocks irrespective of soil type and precipitation regimes. ~~-~~We primarily attribute these large SOC losses to the frequent tilling and low organic matter inputs. Tillage exposes SOC to microbial activity through the destruction of aggregates which as a result makes SOC complexes vulnerable to decomposition (Six, et al., 2002; Mangalassery et al., 2013). Furthermore, <u>fine grained particles (such as clay) and </u>~~SOC~~<u>associated organic matter </u>~~stocks in agriculture systems~~ can also be lost through <u>soil </u>erosion, runoff and leaching <u>(Gonzalez and Laird, 2003) </u>due to a lack of soil protection measures especially following plowing at the onset of the monsoon (Dourte et al., 2012). -Associated with the erosional clay losses is a corresponding reduction of the soil's carbon storage potential. However, since all our plots were established on flat to gentle slopes, and because we were only on-site for one day ~~erosion is of minor importance~~we did not measure soil erosion.

As previously reported by van Straaten et al. (2015), we also found that SOC stock losses were proportional to the initial forest SOC stock, whereby the higher the SOC stock was initially, the larger the corresponding SOC stock loss when converted to agriculture (Fig. A4, Appendix A).

4.3 SOC stocks rebound when agroforestry systems are established

Increases in SOC stocks resulting from agroforestry establishment are ultimately attributed to higher organic matter inputs from above- and belowground sources (leaves, wood, roots, fungi, animals, etc.; Montagnini and Nair, 2004) and a reduction of SOC losses from decomposition and leaching. Similar to the carbon stocks in forests, MAP, basal area, clay fraction and pH also control carbon stock changes when agricultural land is converted to agroforestry (Table 2, Fig. 4 e-h). Furthermore, the accumulation of SOC depends highly on the quality of incoming litter (Lemma et al., 2006) and is reflected in the significantly higher soil C:N ratios in homegarden, coconut and mango AFSs (Fig. A5, Appendix A). In comparison to litter from agricultural crops, which generally have low C:N ratios and decompose rapidly, organic matter inputs from trees are generally of poorer quality (higher C:N ratios) because of the higher lignin and polyphenolic contents, which in turn results in slower decomposition rates and more SOC accumulation (Davidson and Janssens, 2006).

The large ~~relatively constant~~ SOC stocks increases ~~throughout the soil profile for each respective AFS~~ in the subsoil (Fig. 3) indicate that belowground carbon inputs from roots and/or leaching of organic acids and soluble humus fractions to deeper layers are important processes for SOC accumulation. Considering the trees of the four AFSs have deeper rooting profiles than agricultural crops and that often more than half of the carbon assimilated by trees is transported belowground for root production (Montagnini and Nair, 2004; Poeplau and Don, 2013), it is no surprise that SOC stocks also increased substantially at depth. Furthermore, tillage activities will have mixed soils in the top 30-cm and therein homogenized soil carbon concentrations to a certain extent (Yang and Kay, 2001).

However, the size of the SOC stock change hinges on the type of AFS established and its management practices. While all AFSs gained carbon compared to agriculture, the amounts gained varied strongly between the different types (Fig. 2). While coconut and mango SOC stocks increased just marginally above the agriculture reference, homegarden and coffee SOC stocks rebounded to forest levels. Clearly, the carbon cycling dynamics of both homegarden and coffee AFSs resemble that of natural forests since both AFSs support many different tree species of different ages, have varied stand structures and have high basal areas.

However, not only carbon input, but also losses are a function of AFS type, especially in terms of the plantation management schemes. In coconut and mango AFSs (especially in the dry regions), the low SOC stock increases are linked to the removal of crop residues (including leaves) from the site which are used as fodder or fuel. In coconut, even the tree leaves are removed and utilized.

The effect of climate zone on SOC stock changes can only be quantified within each AFS type. While the climate zone did not affect SOC stock changes in either coffee or homegarden AFSs, only a slight difference were found for coconut and mango (Fig. 2). This is however more likely attributed to the implementation of different management practices and cannot be disentangled from climate itself. For instance, in humid climates coconut farmers utilize a “planted fallow system” which includes a fallow period in the cropping cycle where organic matter is reintegrated into the soil. Such systems have been shown to improve soil fertility and maintain SOC stocks (Salako et al., 1999). In contrast, in the dry sub-humid climate farmers use a continuous cropping system which inevitably results in lower organic matter inputs and therein lower SOC stocks. The age of each respective AFS also had no significant effect on SOC stocks (Fig. 2), indicating that soil carbon had already reached a new equilibrium within the first 30-60 years. This is consistent with literature which report that a new SOC equilibrium can be attained in 20 to 40 years following land-use conversion (Detwiler, 1986; de Blécourt et al., 2013; Chiti et al., 2014).

Lastly, tree species diversity (Shannon Wiener index) correlated strongly positively with SOC stocks in homegarden and coffee AFSs (Fig. 5), highlighting the role that species and resource complementarity have in maximizing biomass production (Cadotte, 2013). Interestingly, both homegarden and coffee AFSs investigated in this study had similar tree diversities as natural forests. Since plant diversity was also positively correlated with basal area (data not shown) it is possible that the favorable climatic conditions where these AFSs exist can allow both high species diversity and high ecosystem productivity. Literature has shown that plant diversity is integrally linked to ecosystem productivity (Cadotte, 2013) and ecosystem resource utilization (Tilman et al., 2012), which both affect SOC storage potential (Thakur et al., 2015). In contrast, monocultures have been shown to have lower organic inputs than species diverse systems (Cardinale et al., 2007)

5 Conclusions

Agroforestry systems provide a unique opportunity to produce food and tree products, while also improving livelihoods, protecting and improving soils and, as discussed here, to sequester carbon. Nevertheless, not all AFSs provide the same benefits. Soils in homegarden and coffee plantations for instance can sequester much more carbon than coconut or mango AFSs. Additionally, the soil carbon sequestration potential of AFSs can be maximized by cultivating a broad range of different tree species, minimizing tillage activities and leaving crop residue on site.

Acknowledgements

We kindly acknowledge financial support from the International Fellowship Program of the Indian Council of Agricultural Research (ICAR), Government of India. We also thank Prof. Dr. N. B. Prakash at the~~,~~ University of Agricultural Sciences in ~~,~~ Bangalore, for his support and guidance and our field assistants Jagadish, M. R. and Sathya.

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Tables

Table 1. Environmental variables and structural characteristics of agroforestry systems in the study area (mean ± SE).

AFS	Climatic zone [*]	Tree / palm species	Soil classification [†]	Elevation (m asl)	MAP [‡] (mm)	MAT [c] (°C)	Clay content [¶] (%)	Tree density [¶] (tree/ha)
Homegarden	Humid	*Artocarpus spp., Mangjfera indica, Myristica spp.* and mixed species	Nitisols (n= 4) Acrisols (n=3)	90 ± 17	3422 ± 277	27.2 ± 0.15	20.8 ± 1.4	362 ± 21
	Moist sub-humid		Nitisols (n=6) Luvisols (n=1)	940 ± 17	1744 ± 52	22.1 ± 0.15	22.6 ± 1.2	328 ± 17
Coffee	Humid	*Artocarpus spp. Terminalia spp.* and mixed forest species	Nitisols (n=4) Acrisols (n=2), Luvisols (n=1)	956 ± 42	2718 ± 90	21.9 ± 0.15	23.1 ± 1.2	291 ± 14
	Moist sub-humid		Nitisols (n=6) Luvisols (n=1)	981 ± 36	1666 ± 61	22.0 ± 0.19	22.1 ± 1.0	285 ± 14
Coconut	Humid	*Cocos nucifera*	Nitisols (n=4) Acrisols (n=3)	90 ± 17	3422 ± 277	27.2 ± 0.15	21.4 ± 1.3	166 ± 6
	Dry sub-humid		Luvisols (n=4) Nitisols (n=3)	860 ± 20	688 ± 49	23.5 ± 0.15	19.4 ± 1.4	177 ± 6
Mango	Dry sub-humid	*Mangifera indica*	Luvisols (n=6) Nitisols (n=1)	875 ± 29	703 ± 29	23.3 ± 0.19	17.9 ± 1.3	104 ± 6
	Semi-arid		Luvisols (n=5) Nitisols (n=2)	844 ± 34	627 ± 28	24.6 ± 0.26	16.9 ± 1.3	116 ± 6

* ICAR, 1984

[†] FAO world reference base soil classification derived from Harmonized World Soil Database (FAO, 2009)

[‡] Derived from WorldClim dataset (Hijmans et. al., 2005) (n=7)

[¶] Mean ± standard error; data derived from respective agroforestry plots (n=14)

Table 2. Multivariate regression models predicting SOC stocks in different land-use systems and the relative changes in SOC stock (%) from either forest or agriculture references in the 100 cm soil profile. MAP is mean annual precipitation (mm), MAT is mean annual temperature (°C), Clay fraction (%) and basal area (m^2 ha^{-1}).

Land-use	**Statistical model**	**R^2**	**n**
	SOC stock (Mg C ha^{-1})		
Forest	SOC stock = 71.7 + 4.9(Basal area) – 4.3(MAT) + 1.6(Clay) + 9.0(pH) + 0.006(MAP)	0.82**	56
Homegarden	SOC stock = 95.1 + 3.5(Basal area)	0.29**	28
Coffee	SOC stock = 680.5 + 4.5(Basal area) + 4.2(Clay) – 34.7(MAT) + 0.03(MAP)	0.64**	28
Coconut	SOC stock = –186.7 + 11.5(MAT) – 1.1(pH)	0.40**	28
Mango	SOC stock = 42.3 + 4.3(Basal area)	0.34**	28
Agriculture	SOC stock = –25.1 + 4.4(Clay) + 0.006(MAP)	0.47**	56
	Relative change in SOC stock (%) from forest to agriculture		
Agriculture	ΔSOC = -144.8 + 2.1(Clay) + 2.1(MAT)	0.34**	56
	Relative change in SOC stock (%) from agriculture to AFS		
All AFSs	ΔSOC stock = 228.8 + 2.7(Basal area) -8.9(MAT) + 0.01(MAP)	0.15**	92
Homegarden	ΔSOC stock = 228.3 + 7.1(Clay) – 4.8(Basal area) – 37.1(pH)	0.29**	27
Coffee	ΔSOC stock = -8.7 - 7.1(Basal Area) + 7.7(Clay)	0.44	9
Coconut	ΔSOC stock = -223.5 + 6.3(Basal area) + 0.002(MAP) + 24.7(pH)	0.24†	28
Mango	ΔSOC stock = -66.7 + 13.9(Basal area) - 0.2(MAP) + 30.6(pH) - 3.0(Clay)	0.58**	28

[†] marginally significant at p ≤ 0.1, * significant at p ≤ 0.05 and ** highly significant at p ≤ p ≤ 0.01

Figures caption

Figure 1. ~~-~~Geographical location of the plot clusters in southern India. Each point represents a cluster of four plots: natural forest, agriculture and the AFSs at two ages (medium and old).

Figure 2. ~~Mean~~ Absolute SOC stocks (0-100 cm) in the four different land-use systems. Each~~,~~ ~~with each~~ graph shows~~ing~~ the respective forest and agriculture references and the two AFSs ages categories (medium and old) in the two different climatic zones. ~~Each p~~Point represents the mean of seven plots, while error bars indicate the 95% confidence intervals based on the Student's T distribution. Within each graph the letters indicate significant differences ($P<0.05$; one-way ANOVA) between land-use systems for each climate zone. ~~The arrows with corresponding numbers indicate the trajectory of the land-use change and the number of plots originating from the respective references.~~

Figure 3. Relative change in SOC stock in the 1-m soil profile from agriculture to agroforestry systems (homegarden (△; n=27), coffee (□; n=9), coconut (◆; n=28) and mango (▼; n=28). Error bars indicate the 95% confidence intervals based on the Student's T distribution. The numbers in the grey shaded area show the ~~Cumulative increase~~ absolute changes in ~~in~~ SOC stocks (Mg C ha^{-1}) (n.s. = not significant). The numbers in brackets indicate the corresponding carbon change in percent of the overall change in the soil profile. ~~(considering only the depths with significant changes). The magnitude of SOC stock increases for depths where significant changes are presented are presented in the gray-shaded area. (n.s. = not significant).~~

Figure 4. Scatterplots (a-d) showing the relationship forest SOC stock (top 1m) exhibits with MAP (mm), basal area (m^2 ha^{-1}), soil texture (clay percent), and soil pH across humid (□), moist-sub-humid (●), dry sub-humid (△) and semi-arid (+) climate zones. Scatterplots (e-h) show the relationship SOC stock changes (from agriculture reference) have with the same soil and biophysical variables in homegarden (△), coffee (□), coconut (◆) and mango (▼) AFSs.

Figure 5. Scatterplot showing the relationship SOC stock of homegarden and coffee AFSs exhibits with plot Shannon Wiener species diversity index: homegarden in the humid zone (▲) and moist sub-humid zone (△) and coffee in the humid zone (■) and moist sub-humid zone (□).

Appendix A

Figure A1. Photos of the six land use types investigated in two climatic zones.

Figure A2. Scatterplot showing the relationship between basal area (m^2 ha^{-1}) and MAP (mm) across humid (□), moist-sub-humid (●), dry sub-humid (△) and semi-arid (+) climate zones.

Figure A3. Scatterplots showing the relationship (or lack thereof) between MAT (°C) and (a) forest SOC stocks across humid (□), moist-sub-humid (●), dry sub-humid (△) and semi-arid (+) climate zones and (b) changes in SOC stocks in in homegardens (△), coffee (□), coconut (◆) and mango (▼) AFS.

Figure A4. a) Agriculture SOC stocks (●) in comparison to forest reference SOC stock in the 100 cm soil profile. The slope of the linear regression (m) that differed significantly from one highlight an uneven response of carbon loss or gain as affected by the initial SOC stocks. The stars, ** indicates that the linear regression slope is significantly different from one (P <0.01).

Figure A5. Relative change in C/N ratio in the 1-m soil profile from agriculture to agroforestry systems (homegarden (△; n=27), coffee (□; n=9) coconut (◆; n=28) and mango (▼; n=28). Error bars indicate the 95% confidence intervals based on the Student's T distribution.