CHAPTER

3

Organic Carbon Stocks in all Pools Following Land Cover Change in the Rainforest of Madagascar

Mieja Razafindrakoto[*], *Andry Andriamananjara*[*], *Tantely Razafimbelo*[*], *Jennifer Hewson*[†], *Riana H. Andrisoa*[*], *Julia P.G. Jones*[‡], *Ilja van Meerveld*[§], *Alison Cameron*[‡], *Ntsoa Ranaivoson*[*], *Nandrianina Ramifehiarivo*[*], *Nantenaina Ramboatiana*[*], *Ravo N.G. Razafinarivo*[¶], *Tahiana Ramananantoandro*[¶], *Andriambolantsoa Rasolohery*[**], *Marie P. Razafimanantsoa*[*], *Christophe Jourdan*[††], *Laurent Saint-André*[††], *Gabrielle Rajoelison*[¶], *Herintsitohaina Razakamanarivo*[*]

[*]Laboratoire des Radioisotopes, Antananarivo, Madagascar [†]Conservation International, Arlington, VA, United States [‡]Bangor University, Bangor, United Kingdom [§]University of Zürich, Zürich, Switzerland [¶]Ecole Supérieure des Sciences Agronomiques—Département Eaux et Forêts, Antananarivo, Madagascar [**]Conservation International, Antananarivo, Madagascar [††]Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Montpellier, France

INTRODUCTION

Terrestrial ecosystems represent the most important carbon (C) sink with their capacity to store almost three times that of the atmosphere (Trumper et al., 2009). Further, approximately 40% of terrestrial C is stored in tropical forests, sequestering large amounts of carbon dioxide from the atmosphere (Beer et al., 2010; Pan et al., 2011). However, these forests are threatened

Soil Management and Climate Change
https://doi.org/10.1016/B978-0-12-812128-3.00003-3

by high rates of conversion to other land uses, constituting a major source of greenhouse gas (GHG) emissions and contributing to climate change (Fearnside, 2000; Houghton, 2005). The UN initiative, Reducing Emissions from Deforestation and Forest Degradation (REDD+), represents one path aimed at mitigating the impacts of climate change by conserving tropical forests threatened by deforestation or degradation (Day et al., 2013). It aims to reduce carbon dioxide emissions from developing countries through the sustainable management of forests, while providing co-benefits of biodiversity conservation and livelihood support (Danielsen et al., 2011). Accurate carbon stock quantification represents one important step in ensuring the successful implementation of REDD+, as such information is needed for validation and verification of emissions reductions. (Gibbs et al., 2007; Saatchi et al., 2011).

In eastern Madagascar, deforestation is mainly due to slash-and-burn agriculture (Styger et al., 2007), which results in a mosaic of land use types where fallows are prevalent (Nambena, 2003). To address deforestation in one area of this region, many activities have been implemented, including the development of a REDD+ project initiated by the Government of Madagascar in 2008 (Conservation International, 2013). REDD+ demands a precise estimation of the amount of C stored in forest and other land use types in order to accurately calculate, for example, the emissions avoided due to the presence of a REDD+ project (Andriamananjara et al., 2016). This is needed because the contribution of the C pools may vary across the landscape. The majority of studies to date on C accounting in different forest ecosystems in Madagascar considered separately the C pools, while studies of the estimation of C stock that consider all five C pools are scarce (Andriamananjara et al., 2016; Grinand et al., 2017; Razakamanarivo et al., 2011, 2012).

In this chapter, we firstly review a recent study that accounted C stocks in all five pools recognized by the IPCC (2003), including AGB, BGB, litter, deadwood (DW), and SOC. Afterwards, we identify their dynamics across land uses following deforestation.

MATERIALS AND METHODS

Study Sites

The study was conducted in the Corridor Ankeniheny-Zahamena forest (CAZ), a humid tropical rainforest in the eastern region of Madagascar. As reported by Andriamananjara et al. (2016), the CAZ extends over 371,000 ha, representing an important remnant of evergreen rainforest of Madagascar. This rainforest (closed-canopy forest) is the original vegetation type and provides ecosystem services for many communities surrounding CAZ, such as water supply, erosion control, regulation of the climate (Conservation International, 2013). In addition to the forest, the landscape is characterized by a mosaic of postdeforestation land uses with specific vegetation compositions. As described by Styger et al. (2007), after the first deforestation, fallow is dominated by trees, especially *Trema orientalis* and *Harungana madagascariensis;* this is termed the tree fallow (TF) stage. The second stage is the shrub fallow (SF) resulting from the second to the fourth cycles of forest clearance. Here the endemic shrub species, *Psidia altissima* become the dominant species followed by *Rubus moluccanus*, *Lantana camara*, and *Aframomum angustifolium*. The fifth cycle is characterized by the fern species: *Pteridium aquilinum* and *Sticherus flagellaris*. After the sixth cycle, *Imperata cylindrica* become the characteristic species. This last stage is characterized as degraded land (DL). Thus, four land uses were considered in this study: closed canopy (CC), tree fallow (TF), shrub fallow

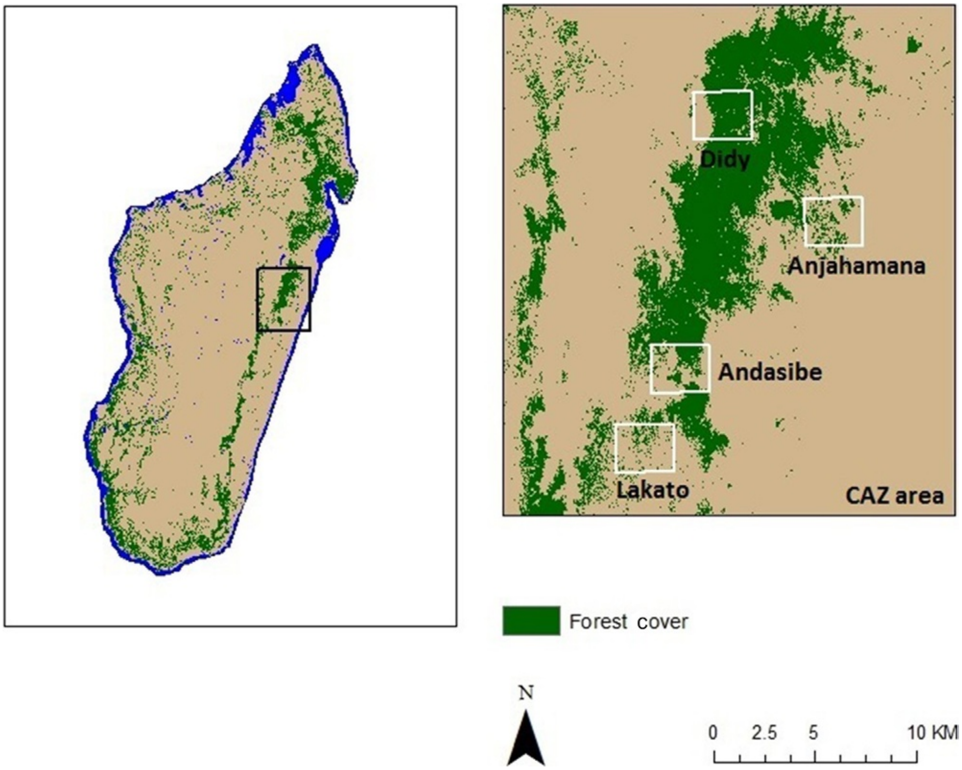

FIG. 1 Location of regions surveyed for carbon quantification.

(SF) and degraded land (DL). These land uses were identified by prior remote sensing and geographic information system GIS analysis, botanical indicator species inventories, and interviews with local people regarding the land use history in the field.

The corridor was stratified based on a remote sensing and GIS analysis, and four representative zones were selected including: *Lakato*, *Andasibe*, *Anjahamana* and *Didy* (Fig. 1). The minimal area for surveys in forest ecosystem is reported to be at least 1 ha to cover the species representation in the study area (Rajoelison, 2005).

It is to be noted that multiple criteria were considered during prior remote sensing and GIS analysis, such as: deforestation history, altitude, slope, bioclimatic subdivision, soil type, accessibility, and river network. A total of 123 sites including the four land uses types were surveyed all along the CAZ (Table 1).

Quantification of Carbon Stocks

The quantification of C stock for AGB in trees with diameter at breast height (DBH) > 5 cm was based on a tree inventory within a 20 m radius circular plot (Fig. 2). The following information was recorded: species name, DBH (the tree diameter at 1.30 m above the soil), and tree height (H). The wood specific gravity (WSG) was also determined.

TABLE 1 Number of Surveyed Sites Per Land Use Type

Zone of Interest	CC	TF	SF	DL	TOTAL
Lakato	7	7	7	7	28
Andasibe	9	9	11	10	39
Anjahamana	7	7	7	7	28
Didy	7	7	7	7	28
TOTAL	30	30	32	31	123

CC: closed canopy; TF: tree fallow; SF: shrub fallow; DL: degraded land.

The allometric equation (Eq. 1) proposed by Chave et al. (2014), representing the most recent model developed for tropical forests including Madagascar, was applied:

$$AGB = 0.0673 \times (WSG \times DBH \times DBH \times H)^{0.976} \tag{1}$$

For saplings (small trees with DBH < 5 cm and H > 1.30 m), each species was counted within a 2 m radius plot. Five different species of saplings were then chosen randomly and weighed and sampled.

For the other AGB subpools, including understory vegetation and herbaceous biomass, the C stock was estimated by weighing all vegetation within a 1 m × 1 m quadrate in four subplots (Andriamananjara et al., 2016).

Following Andriamananjara et al. (2016), soil sampling up to 100 cm depth for each sampling plot (Fig. 2) was completed using a manual steel auger for bulk density measurement and a steel cylinder for carbon content analysis. Walkley and Black (1934) method and mid-infrared spectroscopy (MIRS) model were used to determine the soil carbon content. The SOC stock was calculated according to Parras-Alcántara et al. (2013).

For the BGB assessment, root sampling, including coarse (diameter > 10 mm) and medium roots (diameter between 2 mm and 10 mm), was performed using a 1 m × 1 m pit.

For the litter biomass quantification, litter was sampled at the same location used for the understory and herbaceous sampling (Fig. 2). The leaf litter and root mat within a 0.25 m × 0.25 m quadrate was collected and weighed. Collected biomass samples were generally oven-dried at 75°C over a 48-h period in order to determine the dry biomass content.

For deadwood (composed of standing and lying dead wood), the method proposed by Winrock international (Pearson and Brown, 2005; Walker et al., 2012) was used. The standing deadwood measurement followed the same plot design used for the trees. The diameter at the base, DBH, the diameter of the top, and the height of each standing deadwood were recorded. The volume of standing deadwood was obtained with Eq. (2):

$$\text{Volume}(m^3) = 1/3 \times \pi \times H \times (r_1^2 + r_2^2 + r_1 \times r_2) \tag{2}$$

where H is the total height of the standing deadwood, r_1 is the diameter at the base, and r_2 corresponds to the diameter at the top.

For lying deadwood, the diameter for each individual crossing a transect of 100 m length through the center of the tree plot was measured (Fig. 2). For each individual piece of

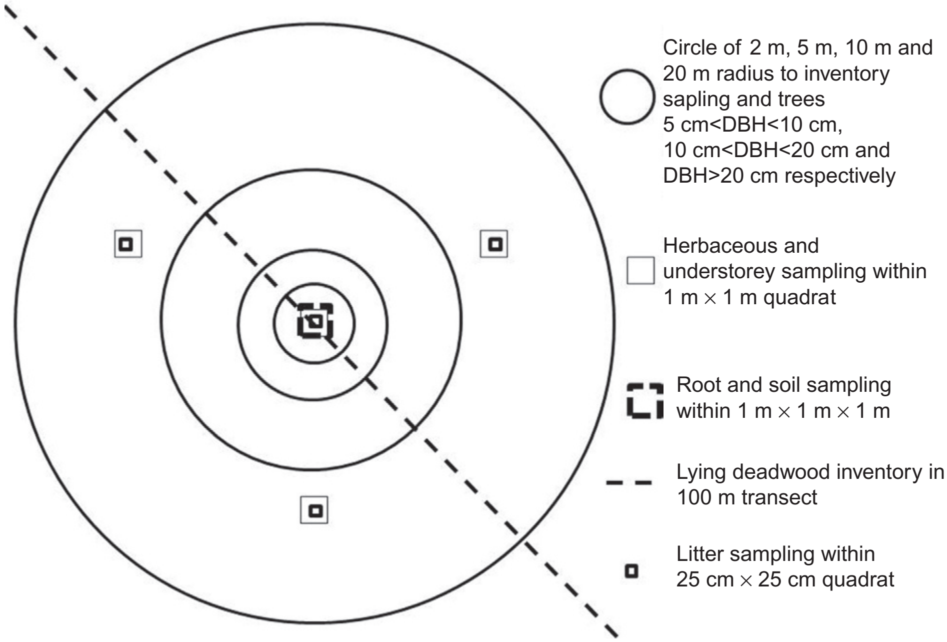

FIG. 2 Sampling design for carbon quantification of each pool for all land uses.

deadwood, both standing and lying, the density of the wood was recorded. Eq. (3) was used to determine the volume of lying deadwood:

$$\text{Volume}\left(\text{m}^3\right) = \pi^2 \times \left(\left(d_1^2 + d_2^2 + \cdots + d_n^2\right) / 8 \times L\right) \tag{3}$$

where d_i is the diameter intercepting the transect and L is the length of the transect, which corresponds to 100 m.

The biomass of deadwood is obtained with Eq. (4):

$$\text{Biomass} = \text{Volume} \times \text{Density} \tag{4}$$

The wood density was classified as sound (S), intermediate (I), and rotten (R). We applied the same wood density values for each class as identified in the project description document (PDD) developed for the REDD+ project. These values correspond to 0.76, 0.58, and 0.48 for the S, I, and R categories, respectively. The C conversion rate of 0.5 (Brown, 2002) was applied to convert biomass into C stock throughout the study.

Statistical Analysis

Descriptive statistics of C stock and the contribution of each pool to the total C stock were used to assess the variability of data. The statistical significance of differences in the contribution of each pool to the total C stock, as well as in changes of the C stock of each pool following land degradation, were tested using ANOVA followed by the Student-Newman-Keuls (SNK) multicomparison test. To assess the contribution of each pool to the total carbon stock, analyses were performed for each land use and for all land uses together. All analyses were performed using R software 3.1.3 (Auguie, 2012; R Core Team, 2015; Wickham, 2009; Felipe de Mendiburu, 2012).

RESULTS

Contribution and Importance of Each Carbon Pool to the Total Carbon Stock

Fig. 3 reports the importance of each carbon pool to the total C stock. For the ensemble of land uses, results show the large contribution of the SOC pool up to 100 cm depth (76.49% corresponding to 135.08 Mg C ha^{-1}), followed by the AGB pool (13.54% corresponding to 30.98 Mg C ha^{-1}), to the total C stock in all land uses.

In CC the SOC stock up to 100 cm depth averaged 51.35% (corresponding to 144.35 Mg C ha^{-1} on average) of the total C stock. Following deforestation, the proportion of SOC, compared to other C pools, increases as the land degrades, reaching 87.19% of the total C stock in DL lands (Fig. 3).

Considering the vertical distribution of SOC along the soil profile, it was found that the topsoil at 0–30 cm depth held a larger proportion of SOC (66.88% of the 0–100 cm SOC profile), compared to the deeper soil layer from 30 to 100 cm depth; the deeper soil layer held only 33.12%. Further, the amount of carbon stored in the topsoil (0–30 cm depth) ranged from 35.74 Mg C ha^{-1} to 167.35 Mg C ha^{-1} and from 2.85 Mg C ha^{-1} to 156.78 Mg C ha^{-1} for deep soil (30–100 cm depth) (Table 2).

While the AGB C pool represented the second highest contributor to the total C stock after the SOC pool, the contribution of this pool decreased following a land use change from CC to fallows and, eventually, DL. Actually, AGB ranged from 30.85% of the total carbon stock for closed canopy to 5.99% for degraded lands with an average of 13.53% among all land uses

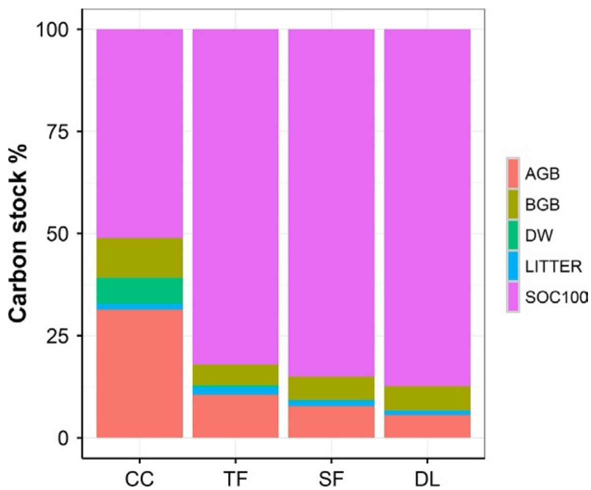

FIG. 3 Contribution of each carbon pool to the total carbon stock.

TABLE 2 Carbon Stocks (Mg ha^{-1}) Per Subpool According to Land Use Type

LU	ABG			Litter		DW		BGB		SOC Up to 100 cm	
	Tree	Sapling	Herbaceous	Leaf_litter	Root_mat	Standing_ DW	Lying_DW	Coarse_root	Medium_ root	SOC30	SOC30-100
All land use	21.10 ± 40.45	1.89 ± 2.29	7.92 ± 6.56	1.98 ± 1.16	0.65 ± 0.82	1.71 ± 4.30	3.06 ± 6.57	7.45 ± 7.99	5.73 ± 7.53	87.84 ± 22.79	47.23 ± 25.84
CC	82.81 ± 40.44	2.778 ± 1.99	2.93 ± 2.35	2.474 ± 0.69	1.51 ± 1.02	6.21 ± 6.78	11.99 ± 7.93	15.50 ± 11.13	11.76 ± 12.22	93.33 ± 30.08	51.02 ± 26.31
TF	3.57 ± 5.40	3.419 ± 2.98	9.71 ± 7.135	2.38 ± 0.98	0.49 ± 0.54	0.36 ± 1.10	0.55 ± 3.01	4.24 ± 3.82	3.72 ± 3.32	82.09 ± 15.70	47.93 ± 27.06
SF	0.14 ± 0.39	1.46 ± 1.36	10.46 ± 7.22	1.81 ± 0.82	0.28 ± 0.33	0.42 ± 1.65	0 ± 0	5.57 ± 4.89	3.38 ± 2.69	89.79 ± 20.26	44.90 ± 26.09
DL	0 ± 0	0 ± 0	8.39 ± 5.58	1.28 ± 1.57	0.37 ± 0.56	0 ± 0	0 ± 0	4.70 ± 3.80	4.28 ± 4.43	86.09 ± 22.44	45.30 ± 24.71

Means ± SEs; Coarse root: root diameter higher than 10 mm; medium root: root diameter between 2 and 10 mm; SOC30: SOC stock in 0–30 cm depth; SOC30-100: SOC stock in 30–100 cm depth. All land use: all 123 sites, not considering the specific land use of each one.

(Fig. 3). The total C stock in the AGB pool ranged from 88.52 Mg C ha^{-1} in closed canopy to 8.39 Mg C ha^{-1} in degraded lands. Here, the AGB carbon stock values were obtained from different carbon subpools including: the tree carbon stock, the understory vegetation carbon stock, and the sapling carbon stock. In the surveyed closed-canopy forest, AGB is stored mainly in trees with DBH greater than 5 cm (with 82.81 Mg C ha^{-1} representing 93.16% of the total AGB C stock) while in other land uses, herbaceous vegetation represents the majority of the AGB C stock (with 9.71 Mg C ha^{-1} in TF, 10.46 Mg C ha^{-1} in SF, and 8.39 Mg C ha^{-1} in DL corresponding respectively to 57.93%, 80.60%, and 100% of the total AGB C stock).

The contribution of BGB to the total carbon stock is also significant, as reported in Fig. 3. Considering all land uses, BGB averaged 6.64% of the total C. This BGB C stock showed significant ($P < 0.001$) variations across the land use gradient. In closed canopy, BGB held 9.67% of the total carbon stock, ranging from 5.55 to 68.46 Mg C ha^{-1}, while in tree fallow, BGB represented 5.01% of the total carbon stock, ranging from 0.54 to 22.53 Mg C ha^{-1}. In shrub fallows and degraded land, the BGB carbon pool was as important as the AGB carbon. No significant difference ($P > 0.1$) was found between AGB and BGB carbon stock of both the shrub fallow and degraded land.

The contribution of the DW carbon pool was found to be significantly different in a closed-canopy forest than in nonforest land uses. In closed canopy, the carbon stock in the DW pool represented an average of 6.64% of the total carbon stock, ranging from 2.97 to 58.30 Mg C ha^{-1}. A decreasing trend in the contribution of the deadwood C pool was observed along the land use change in degradation pathways, from closed canopy to degraded land ($P < 0.001$) (Fig. 3).

The litter carbon pool represented the lowest contribution to total carbon stock (Fig. 3). As reported in Fig. 3, the proportion of the litter carbon pool differed according to the land use, with the lowest contribution in the degraded land use, representing just 1.27% of the total C stock, and the highest contribution in the tree fallow land use, representing 1.89% of the total C stock. The highest litter C stock value was observed in closed canopy, with an average value of 3.98 Mg C ha^{-1}; the lowest litter C stock values were observed in degraded land, with an average of just 1.65 Mg C ha^{-1}.

Considering total carbon in the visible (AGB, DW, and litter) and hidden pools (BGB and soil organic matter), as illustrated in Fig. 4, carbon is preferentially stored in the underground pools in all land uses.

This contrast is more observed for the nonforest land uses, averaging 140.67 Mg C ha^{-1} for the hidden pool and 15.03 Mg C ha^{-1} for the visible pool. In closed canopy, the difference is less marked, with an average carbon stock value of 171.62 Mg C ha^{-1} in the below-ground pool and 110.69 Mg C ha^{-1} in the above-ground pool.

Dynamic of Each Carbon Pool Following Land Use Change

Among the five carbon pools, four pools showed significant ($P < 0.001$) variations across the land use degradation gradient, including AGB, BGB, DW, and litter, as illustrated in Fig. 4. Conversely, no significant change of SOC stock distribution was found with land use change.

A decreasing trend of AGB carbon stock was observed from closed canopy (with an average value of 88.52 Mg C ha^{-1}) to tree fallows (16.70 Mg C ha^{-1}); the transition of shrub fallow to degraded land showed a relatively small decrease of AGB, from 12.06 to 8.39 Mg C ha^{-1}.

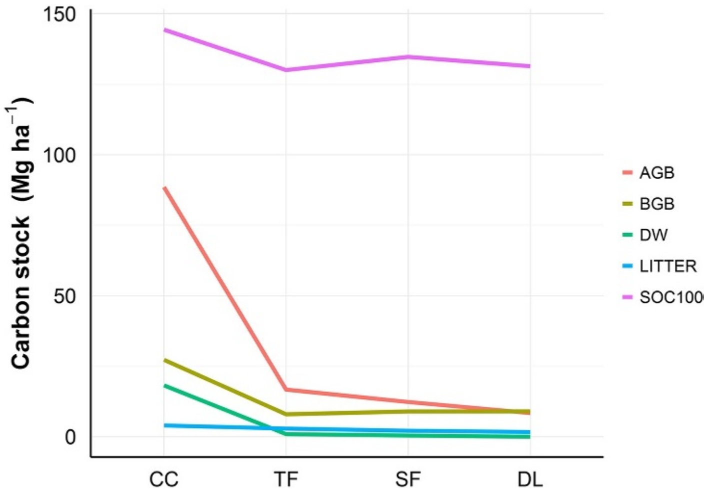

FIG. 4 Variation of each pool according to land use.

The BGB and DW pools followed the same pattern as the AGB pool: a major decrease from forest to tree fallows and a less marked variation between the other land uses (Fig. 4). For the litter, significant decreases of carbon stock ($P < 0.001$) were observed from closed canopy (3.98 Mg C ha^{-1}) to tree fallow (2.87 Mg C ha^{-1}) to shrub fallow (2.09 Mg C ha^{-1}).

DISCUSSION

Contribution and Importance of Each Pool

This study showed that SOC was the most important carbon pool, storing the largest proportion of carbon among the different carbon pools and being the largest carbon stock regardless of land use. Different studies have found similar results, finding that soil can store two to three times more carbon than the vegetation they support (Grinand et al., 2009, O'Keefe et al., 2010; Scharlemann et al., 2014). The SOC contribution to the total carbon stock increased with land use degradation, from 51.35% in the forest to 87.19% in degraded land. This could be explained by the relative stability of the soil pool compared to the above-ground and below-ground biomass across the land use degradation pathway (Sierra et al., 2007). As reported above, the SOC didn’t change significantly following land degradation, which is contrary to the above-ground biomass carbon stock that varied highly from the conversion of forest to fallow.

After the SOC, the AGB contributed the second-highest proportion to the total C stock. Trees represented the main component of the vegetation biomass in the forests in this study, storing a large amount of carbon with an average of 82.80 Mg C ha^{-1}; in other land cover types, the AGB is essentially composed of small trees, shrubs, and herbaceous vegetation. These vegetation types stored less carbon than the forest, varying from 0.86 to 31.37 Mg C ha^{-1} in DL, from 3.08 to 30.09 Mg C ha^{-1} in SF, and from 1.49 to 35.97 Mg C ha^{-1} in TF.

In herbaceous (SF and DL) land uses, the contribution of AGB and BGB were not significantly different. According to Poorter et al. (2012), plants will preferentially allocate more biomass to roots if the limiting factor for growth is below ground (e.g., nutrients, water), whereas they will allocate proportionally more biomass to shoots if the limiting factor is above ground (e.g., light, CO_2). Therefore the relative importance of the BGB carbon pool slightly depends on these conditions. Here, the BGB result was produced by a BGB survey using the classical method of digging a pit of standard size. Other in-depth work on BGB used the specialist "voronoi" method to show that BGB can be important in tropical forest ecosystem.

Dynamic of Each Pool Following Land Use Change

In terms of variation along the land use degradation pathway, soils are a relatively stable pool, and deep SOC (30–100 cm) is considered relatively more stable than topsoil carbon (Harrison et al., 2011). As carbon from a 30–100 cm depth represents 33.12% of the total assessed SOC, this could be adding more stability to the SOC pool. Randrinarisoa et al. (2014) found no significant variation of carbon stock in the SOC between forests and other land uses following deforestation, inducing only a small variability in SOC in response to land use change.

In contrast to the SOC pool, the AGB biomass and DW carbon pools are more likely to change across the degradation pathway, especially during the forest-to-nonforest land use transition. In eastern Madagascar, the main land use change driver is reported to be slash-and-burn agriculture (Tsujimoto et al., 2012), and the frequent use of fire is replacing native species with exotic and aggressive ones, favoring grasses over woody species and creating treeless landscapes (Styger et al., 2007). This change in the floristic composition affects the biomass production and therefore the variation of C stock in the AGB pool.

BGB followed the same decreasing pattern as AGB after the conversion of forest to nonforest land uses. However, the BGB trend seems to show some recovery of the carbon stock along the degradation trajectory, although it is not significant between nonforest land uses. This BGB could be considered as stable or slightly varying in response to environmental factors. This relative stability could be explained by the similarity of the vegetation type in the degraded land uses. In the nonforest land uses, the vegetation cover is mainly composed of herbaceous plants, which could produce a large amount of roots, especially fine roots. For both SF and DL the percentage of herbaceous plants are very high (80.60% and 100% of total AGB, respectively) but in TF, this percentage is lower (57.93% of total AGB). The sampling design of BGB could explain the similarity in root carbon stocks between these land uses. In TF, trees are scarce and herbaceous vegetation is more widespread. The root sampling pits could be relatively far from the trees, thus leading to unsampled tree roots and leaving only the herbaceous plants' roots to be sampled. However, the BGB pool could influence the evolution of the SOC pool, as it could store the below-ground carbon from roots. In this study, the SOC was considered up to 1 m depth. Deep-soil carbon is known to be more stable than topsoil carbon. Dead roots could supply C to the soil by microbial conversion; moreover Fang et al. (2015) described the SOC, which originated from fine root decomposition as an important source of deep SOC.

CONCLUSION

This study highlights that SOC up to 100 cm is the most important pool in terms of contribution to the total C stock and amount of carbon. The AGB pool represents the second most important pool, in terms of contribution to the total C stock, characterized by a significant decrease, especially from forest to nonforest land uses. The SOC and AGB pools are followed by the BGB pool in CC and TF, while this pool contains as much carbon as the AGB pool in the two other land uses (SF and DL). However, an in-depth BGB survey with specific methods such as local allometric equations is required to accurately estimate the root carbon stock, which is reported to be an important pool in tropical forest ecosystems. Concerning the effect of deforestation on the dynamic of each C pool, results showed that all pools except the SOC varied across land use. Therefore considering these decreasing pools, C mapping is important in the context of REDD+ implementation. Further mapping of C stock on regional and national scales based on these five C pools would constitute valuable scientific knowledge for decision making in land management policies.

Acknowledgments

This work is funded by the ESPA program as part of the p4ges project (grant references: NE/K008692/1, NE/K010115/1, and NE/ K010220-1). The authors acknowledge L'Homme et l'Environnement Association, Mitsinjo Association, Groupe d'études et de recherche sur les primates (GERP), and the ESSA-Forêts team for their collaboration. We are very grateful to local communities in Lakato, Andasibe, Anjahamana, and Didy and to all field teams for their help during data collection.

References

Auguie, B., 2012. gridExtra: Functions in Grid Graphics. R Package Version 0.9.1. http://CRAN.R-project.org/package=gridExtra.

Andriamananjara, A., Hewson, J., Razakamanarivo, H., Andrisoa, R.H., Ranaivoson, N., Ramboatiana, N., Razafindrakoto, M., Ramifehiarivo, N., Razafimanantsoa, M.-P., Rabeharisoa, L., Ramananantoandro, T., Rasolohery, A., Rabetokotany, N., Razafimbelo, T., 2016. Land cover impacts on aboveground and soil carbon stocks in Malagasy rainforest. Agric. Ecosyst. Environ. 233, 1–15.

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rödenbeck, C., Arain, M.A., Baldocchi, D., Bonan, G.B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K.W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F.I., Papale, D., 2010. Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. Science 329, 834–838.

Brown, S., 2002. Measuring carbon in forests: current status and future challenges. Environ. Pollut. 116, 363–372.

Chave, J., Méchain, M., Burquez, A., Chidumayo, E., Colgan, M., Delitti, W., Colgan, Matthew S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob. Chang. Biol. 20, 3177–3190.

Conservation International, 2013. Carbon emission reduction project in the corridor Ankeniheny-Zahamena (CAZ) protected area, Madagascar. MONITORING REPORT: VCS Version 3.

Danielsen, F., Skutsch, M., Burgess, N.D., Jensen, P.M., Andrianandrasana, H., Karky, B., Lewis, R., Lovett, J.C., Massao, J., Ngaga, Y., Phartiyal, P., Poulsen, M.K., Singh, S.P., Solis, S., Sørensen, M., Tewari, A., Young, R., Zahabu, E., 2011. At the heart of REDD+: a role for local people in monitoring forests? Conserv. Lett. 4 (2), 158–167.

Day, M., Baldauf, C., Rutishauser, E., Sunderland, T.C.H., 2013. Relationships between tree species diversity and above-ground biomass in Central African rainforests: implications for REDD. Environ. Conserv. 41 (1), 64–72.

Fang, X.-M., Chen, F.-S., Wan, S.-Z., Yang, Q.-P., Shi, J.-M., 2015. Topsoil and deep soil organic carbon concentration and stability vary with aggregate size and vegetation type in subtropical China. PLoS ONE 10 (9).

Fearnside, P.M., 2000. Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Clim. Change 46 (1–2), 115–158.

Felipe de Mendiburu, 2012. Agricolae: Statistical Procedures for Agricultural Research. R package version 1, pp. 1–3. Available: http://CRAN.R-project.org/package=agricolae.

Gibbs, H.K., Brown, S., Niles, J.O., Foley, J.A., 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environ. Res. Lett. 2, 045023.

Grinand, C., Rajaonarivo, A., Bernoux, M., Pajot, V., Brossard, M., Razafimbelo, T., Albrecht, A., Le Martret, H., 2009. Estimation des stocks de carbone dans les sols de Madagascar. Etude Gest. Sols 16 (1), 23–33.

Grinand, C., Le Maire, G., Vieilledent, G., Razakamanarivo, H., Razafimbelo, T., Bernoux, M., 2017. Estimating temporal changes in soil carbon stocks at ecoregional scale in Madagascar using remote-sensing. Int. J. Appl. Earth Obs. Geoinf. 54, 1–14.

Harrison, R.B., Footen, P.W., Strahm, B.D., 2011. Deep soil horizons: contribution and importance to soil carbon pools and in assessing whole-ecosystem response to management and global change. For. Sci. 57 (1), 67–76.

Houghton, R.A., 2005. Tropical deforestation as a source of greenhouse gas emissions. In: Moutinho, P., Schwartzman, S. (Eds.), Tropical Deforestation and Climate Change. IPAM and Environmental Defense, Belem, pp. 13–21.

IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Institute for Global Environmental Strategies (IGES), Hayama, Japan, ISBN: 4-88788-003-0.

Nambena, S.M., 2003. Using geographic information systems to assess possibilities of expanding traditional agroforestry in slash-and-burn zones in Madagascar. Mt. Res. Dev. 23 (4), 329–333.

O'Keefe, P., O'Brien, G., Pearsall, N., 2010. The Future of Energy Use. Earthscan, London.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333, 988–993.

Parras-Alcántara, L., Martin-Carrillo, M., Lozano-Garcia, B., 2013. Impacts of land use change in soil carbon and nitrogen in a Mediterranean agricultural area (Southern Spain). Solid Earth 4, 167–177.

Pearson, T., Brown, S., 2005. Guide de Mesure et de Suivi du Carbone dans les Forêts et Prairies Herbeuses. Winrock International.

Poorter, H., Niklas, K.J., Reich, P.B., Oleksyn, J., Poot, P., Mommer, L., 2012. Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control. New Phytol. 193, 30–50.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.Rproject.org/.

Rajoelison, L.G., 2005. Les forêts littorales de la région orientale de madagascar: vestiges a conserver et a valoriser. Doctoral dissertation, Université d'Antananarivo.

Randrinarisoa, J., Razakamanarivo, H., Rakotondramanana, J., Razafimbelo, T., Andriamananjara, A., Razafimahatratra, H., Ramifehiarivo, N., 2014. Dynamics of soil organic carbon under slash-and-burn agricultural practice in Central Eastern Madagascar. In: International Conference "Agroecology for Africa", 03–07 November, Antananarivo, Madagascar.

Razakamanarivo, H., Grinand, C., Razafindrakoto, M.A., Bernoux, M., Albrecht, A., 2011. Mapping organic carbon stocks in eucalyptus plantations of the central highlands of Madagascar: a multiple regression approach. Geoderma 162, 335–346.

Razakamanarivo, H., Razakavololona, A., Razafindrakoto, M.A., Vieilledent, G., Albrecht, A., 2012. Below-ground biomass production and allometric relationships of eucalyptus coppice plantation in the central highlands of Madagascar. Biomass Bioenergy 45, 1–10.

Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T.A., Salas, W., Zutta, B.R., Buermann, W., Lewis, S.L., Hagen, S., Petrova, S., White, L., Silmana, M., Morel, A., 2011. Benchmark map of forest carbon stocks in tropical regions across three continents. Proc. Natl. Acad. Sci. U. S. A. 108 (24), 9899–9904.

Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R., Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manage. 5 (1), 81–91.

Sierra, C.A., del Valle, J.I., Orrego, S.A., Moreno, F.H., Harmon, M.E., Zapata, M., Colorado, G.J., Herrera, M.A., Lara, W., Restrepo, D.E., Berrouet, L.M., Loaiza, L.M., Benjumea, J.F., 2007. Total carbon stocks in a tropical forest landscape of the Porce region, Colombia. For. Ecol. Manage. 243, 299–309.

Styger, E., Rakotondramasy, H.M., Pfeffer, M.J., Fernandes, E.C.M., Bates, D.M., 2007. Influence of slash-and-burn farming practices on fallow succession and land degradation in the rainforest region of Madagascar. Agric. Ecosyst. Environ. 119, 257–269.

Trumper, K., Bertzky, M., Dickson, B., van der Heijden, G., Jenkins, M., Manning, P., 2009. The Natural Fix? The Role of Ecosystems in Climate Mitigation. A UNEP Rapid Response Assessment. United Nations Environment Programme, UNEP-WCMC, Cambridge, UK.

Tsujimoto, Y., Homma, K., Matsuyama, H., Shiraiwa, T., 2012. Land-use strategies of farmers in responding to rising land-use pressures in the southeastern forest region of Madagascar: a comparative study between lowland households and hillside households. JARQ 46 (3), 249–256.

Walker, S.M., Pearson, T.R.H., Casarim, F.M., Harris, N., Petrova, S., Grais, A., Swails, E., Netzer, M., Goslee, K.M., Brown, S., 2012. Standard Operating Procedures for Terrestrial Carbon Measurement. Winrock International.

Walkley, A., Black, J., 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic titration method. Soil Sci. 37 (1), 29–38.

Wickham, H., 2009. ggplot2: Elegant Graphics for Data Analysis. Springer, New York.