Carbon storage and sequestration of re-growing montane forests in southern Ecuador

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1. Introduction

Tropical montane forests (TMF), defined here as forests between 23.5°N and 23.5°S above 1000 m.a.s.l., make up 8% of the world’s tropical forests by planimetric area (Spracklen and Righelato, 2014). They are widely considered to be important for the provision of ecosystem services, especially water (Bruijnzeel, 2004) and biodiversity (Gentry, 1992; Mittermeier et al., 1999). Recent studies have also highlighted the potential for TMF to store and sequester substantial amounts of carbon (Fehse et al., 2002; Gibbon et al., 2010; Spracklen and Righelato, 2014). Here we report observations of above-ground biomass (AGB) storage within regenerating secondary TMFs in southern Ecuador.

The extent of carbon storage and sequestration in TMF is poorly understood. We quantified the above-ground biomass (AGB) storage in secondary tropical montane forests in southern Ecuador. The AGB in older secondary (>40 years old) forest was found to be 158 ± 38 Mg ha⁻¹ of land surface at 1000 m elevation and 104 ± 25 Mg ha⁻¹ of land surface at 2250 m elevation. This is less than the storage reported in a recent synthesis of AGB observations in mature tropical montane forests, potentially due to a legacy of selective logging within our study sites. The slope angle resulted in AGB being 1.5–10% greater when reported on a planimetric compared to land surface area basis. We also quantified AGB in areas of abandoned pasture where grazing and fire had been excluded. Pasture that had been recently abandoned (1–2 years) stored 2–18 Mg ha⁻¹ of AGB with the higher values due to the presence of relict trees. Regrowing secondary forests, established through natural regeneration, accumulated AGB at a rate of 10 Mg ha⁻¹ yr⁻¹ at 1000 m elevation and 4 Mg ha⁻¹ yr⁻¹ at 2250 m elevation, for the first 5–7 years after pasture abandonment. After 12–15 years, accumulation of AGB slowed to 1–2 Mg ha⁻¹ yr⁻¹. Net biomass accumulation rates were similar to those observed in lowland humid tropical forests, suggesting that regenerating tropical montane forests provide an important carbon sequestration. In newly regenerating forests, small trees (DBH < 10 cm) contributed up to 50% of total AGB. In the older secondary forest at high elevation coarse dead wood contributed 34% of total AGB.

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surrounding forest cover (Bonner et al., 2013). However, the rate of biomass accumulation in secondary forests is poorly quantified in TMFs, with very few previous studies. Fehse et al. (2002) reported that newly (6–8 year) secondary TMF can sequester AGB at a rate of up to 15 Mg ha$^{-1}$ yr$^{-1}$. Gilroy et al. (2014) found that non-soil carbon stocks accumulated at a rate of 4.3 Mg C ha$^{-1}$ yr$^{-1}$ in naturally regenerating montane forests in Colombia. Fast rates of carbon sequestration would make restoration of TMF an important contributor to carbon removal from the atmosphere.

Our objectives in this study were to quantify the above-ground biomass storage in TMF in southern Ecuador and to determine how biomass stocks changed after clearance for agriculture and during recovery of secondary forests after agriculture ceased.

2. Methods

2.1. Study sites

Field work was carried out at two TMFs (Buenaventura and Tapichalaca) in southern Ecuador (Fig. 1). Both forests are owned and managed by the Ecuadorian non-governmental organisation, Fundacion Jocotoco (http://www.fjocotoco.org). The forests are managed with the primary aim of biodiversity protection. Both sites consist of secondary forest and pasture intended for forest regeneration. Secondary forests here are typically abandoned pasture undergoing natural regeneration. Abandoned pasture may account for 35% of total pasture area in montane regions of southern Ecuador (Knoke et al., 2014). Forests at both sites may have been selectively logged in the past. At each reserve we located forest plots in secondary forests of various ages.

Buenaventura Reserve is located near the town of Pinas in the El Oro province of southern Ecuador (3.7°S, 79.7°W). The reserve spans elevations between 400 m and 1200 m altitude on the Pacific slope of the Ecuadorian Andes. Land use in the reserve was at least 90% secondary forest, with very little primary forest remaining. A road that was built through the area in the 19th Century to provide access for machinery for gold mining in the area likely brought about selective logging (N. Simpson, personal communication). In 2011, the reserve covered an area of about 2000 ha. At 1075 m a.s.l., annual mean temperature is 22.5°C and annual mean rainfall is 1475 mm yr$^{-1}$ (Hijmans et al., 2005).

Tapichalaca Reserve is located on the east slope of the Andes adjacent to the Podocarpus National Park (4.5°S, 79.1°W). The reserve spans elevations from 2000 to 3400 m and is about 2000 ha in size. The region is characterised by steep slopes and a high frequency of natural landslides (Moser et al., 2008). At 1900 m a.s.l., annual mean temperature is 18.7°C and annual mean rainfall is 1250 mm yr$^{-1}$ (Hijmans et al., 2005). At the nearby Podocarpus National Park, annual mean temperature (inside the forest, 1.5 m height) decreases from 18.9°C at 1050 m to 8.6°C at 3060 m, while rainfall increases with elevation from 1950 mm yr$^{-1}$ at 1980 m to 4500 mm yr$^{-1}$ at 3060 m (Leuschner et al., 2007). The tree line is typically at 3300–3500 m elevation in the region. Human settlement in the region in the middle of the 20th century likely resulted in selective logging and the extraction of the largest trees.

2.2. Field method

Data was collected during a 3 month period from June through August 2005. We classified each reserve into areas of secondary forest and pasture. Secondary forest existed on areas of abandoned pasture, with forest re-establishing through natural regeneration. We identified areas of secondary forest with ages of 1–15 years since cessation of grazing and burning. The land-use history of each site was determined through interviews with forest guards employed at the reserve. Only areas where at least two forest guards gave a consistent land-use history (estimates of time since abandonment of pasture within 20% of each other) were included in the study. The oldest secondary forest plots were located where there was no visual evidence of human disturbance or landslide activity and no knowledge of clearance within the past 40 years. These plots have secondary forests that are at least 40 years old. Selective logging may historically have occurred in these plots and so they should not be referred to as mature or primary forests. Landslides occur frequently on moderate to steep slopes within the region (particularly at Tapichalaca) and are likely to play a key role in controlling the carbon balance of the forest. However, for the purposes of this work we did not sample areas where landslides were known to have occurred.

Plot establishment and measurement followed the RAINFOR (Red Amazonica Inventarios Forestales, Amazon Forest Inventory Network) guidelines (http://www.geog.leeds.ac.uk/projects/rainfo/index.html; Malhi et al., 2002). One hectare plots ($10,000$ m$^2$ surface area, square $100$ m $\times$ 100 m) were located randomly in secondary forests of different ages (Table 1). The location of plots was identified using GPS. The location, slope and elevation of each plot were recorded. Four secondary forest plots were measured in Buenaventura with ages of 1, 5, 12 and >40 years. Three secondary forest plots were established at Tapichalaca with ages of 2, 15 and >40 years. The >40 year old forest plots at both Buenaventura and Tapichalaca had no known anthropogenic disturbance within the last 40 years and were at least 40 years old.

Biomass was estimated using a non-destructive method. Within each one hectare plot we measured the tree height and diameter at breast height (DBH, 1.3 m above-ground on the uphill side of stem)
Table 1
Age and altitude of forest plots.

| Forest age (years) | Altitude (m) |
|--------------------|--------------|
| Buenaventura       |              |
| 1                  | 550          |
| 5                  | 515          |
| 12                 | 535          |
| 40                 | 1035         |
| Tapichalaca        |              |
| 2                  | 2250         |
| 15                 | 2250         |
| 40                 | 2250         |

of all trees with a DBH greater than 10 cm. The genus of each tree was recorded where this could be identified and trees were tagged with a numbered metal plate at 1.6 m. Location of the trees within the plot was recorded. Lauraceae, Melastomataceae and Rubiaceae were the most frequent tree families recorded at both locations. We measured coarse woody debris (CWD) following the method of Wilcke et al. (2005). Dead wood, standing dead trees and tree stumps were treated as CWD.

Each plot was divided into 20 m × 20 m (400 m²) sub-plots. Five of the sub-plots were selected and within these plots the DBH, tree height and genus of all trees with DBH greater than 2.5 cm was measured. Understorey and ground litter biomass was determined in 1 m² plots in each sub-plot. All living and dead vegetation with DBH less than 2.5 cm was collected and weighed in the field. Superficial soil samples (0–5 cm in mineral soil) were taken from each plot.

2.3. Estimation of biomass

We estimated the biomass in above-ground, below-ground within roots and in CWD. We did not attempt to quantify soil carbon. Understorey and ground litter biomass was not been analysed due to problems with effectively drying biomass samples. In upper-montane forests in Podocarpus National Park, Ecuador, litter has been found to contribute 3–8 Mg biomass ha⁻¹ (Leuschner et al., 2013).

We estimated AGB using existing allometric equations. Allometric equations specific to tree family are currently not available for montane forests in Ecuador so generic allometric equations (Brown, 1997; Chave et al., 2005) were used. We used the allometric equation from Chave et al. (2005) for wet forests where AGB is as a function of tree height (H/m), diameter at breast height (D/cm) and wood density (ρ/g cm⁻³):

\[
AGB = \exp[-2.557 + 0.94 \ln(\rho \times D^2 \times H)]
\]

Chave et al. (2004) make a detailed assessment of the errors associated with calculating AGB from forest plots and allometric equations. We estimate the error in our biomass values using the 24% error reported by Chave et al. (2004) for the combined error due to choice of allometric equation and sampling errors. Calculating AGB using Chave et al. (2005) for moist tropical forests changes our biomass estimates by less than 17%; less than the error we assume in our AGB estimates.

For individual trees where tree height was not recorded it was estimated by fitting a regression between available height and DBH data for that location. We assumed a wood density of 0.571 g cm⁻³, the mean density reported by a study in TMF in Peru (Gibbon et al., 2010). This is approximately 10% lower than the mean wood density of 0.645 g cm⁻³ reported by Chave et al. (2006) for 2456 tree species in Central and South America. We assumed that dry stem biomass consists of 50% carbon by mass (Chave et al., 2005).

Above-ground standing deadwood biomass was calculated in the same way as the AGB in living trees. For both standing deadwood and coarse woody matter we assumed a wood density of 0.31 g cm⁻³ which was the average for coarse woody debris in a montane forest in Ecuador above 2000 m (Wilcke et al., 2005). Below-ground root biomass (fine and coarse roots) was calculated based on AGB according to Cairns et al. (1997):

\[
BGB = \exp[-1.0587 + 0.8836 \ln(AGB)]
\]

This approximates to about 20% of above-ground biomass, consistent with other studies (Leuschner et al., 2013; Moser et al., 2011).

We report AGB as storage per land surface (S) area. We use angle of slope (i) to calculate storage per planimetric (P) area, using the following conversion:

\[ S = P / \cos(i) \]

3. Results and discussion

The biomass storage (per land surface area) calculated at Buenaventura and Tapichalaca Forest Reserves are detailed in Table 2. In >40 year old forest plots we estimated AGB to be 158 ± 38 Mg ha⁻¹ in Buenaventura and 104 ± 25 Mg ha⁻¹ at Tapichalaca, where the error is estimated following Chave et al. (2004). When reported on a planimetric area basis, AGB is 1.5% greater at the forest plot in Buenaventura (slope angle 10°) and 10% greater in the forest plot at Tapichalaca (slope angle 25°).

Fig. 2 shows a comparison of total AGB in >40 year old forest plots in Buenaventura and Tapichalaca compared to a mature TMF (Spracklen and Righelato, 2014). The AGB in both Buenaventura and Tapichalaca is less than mean (271 Mg ha⁻¹) and median (254 Mg ha⁻¹) reported for all TMFs in Spracklen and Righelato (2014). Values reported here are also lower than the mean (247 Mg ha⁻¹, 1σ = 115 Mg ha⁻¹) and median (241 Mg ha⁻¹) values for Neotropical montane forest sites. In Buenaventura, estimated AGB is in the 25th to 50th percentile of Neotropical TMFs reported by Spracklen and Righelato (2014). In Tapichalaca, AGB

Table 2
Biomass storage in Buenaventura (B) and Tapichalaca (T) Reserves. Biomass is reported as storage per hectare of land surface.

| Forest age (years) |              |              |
|--------------------|--------------|--------------|
|                    | 1–2          | 5            |
|                    | 12–15        | >40          |
| Tree (DBH > 10 cm) density (stems ha⁻¹) | B 18 | 104 | 421 | 594 |
|                    | T 71 | – | 396 | 503 |
| Sapling (2.5 cm < DBH < 10 cm) density (stems ha⁻¹) | B 130 | 1830 | 305 | 1145 |
|                    | T 975 | – | – | 1365 |
| Above-ground biomass (brown; DBH > 10 cm) (Mg ha⁻¹) | B 1.3 | 24.0 | 89.4 | 98.5 |
|                    | T 8.7 | – | 57.2 | 65.3 |
| Above-ground biomass (Chave et al., 2005, moist; DBH > 10 cm) (Mg ha⁻¹) | B 1.0 | 28.6 | 128.8 | 134.1 |
|                    | T 7.0 | – | 48.5 | 57.2 |
| Above-ground biomass (Chave et al., 2005, wet; DBH > 10 cm) (Mg ha⁻¹) | B 1.0 | 24.3 | 106.9 | 121.8 |
|                    | T 6.8 | – | 44.9 | 53.5 |
| Above-ground biomass (2.5 cm < DBH < 10 cm) (Mg ha⁻¹) | B 1.7 | 17.6 | 1.6 | 11.6 |
|                    | T 9.2 | – | 10.1 | 15.1 |
| Below-ground root biomass* (Mg ha⁻¹) | B 0.9 | 9.4 | 21.8 | 26.2 |
|                    | T 4.0 | – | 12.0 | 14.6 |
| Dead wood biomass (Mg ha⁻¹) | B 0 | 0 | 1.7 | 24.9 |
|                    | T 2.3 | – | 16.6 | 35.8 |
| Total biomass (Mg ha⁻¹) | B 3.6 | 51.2 | 131.2 | 184.5 |
|                    | T 223 | – | 83.5 | 119.0 |
| Total above-ground biomass* (Mg ha⁻¹) | B 2.7 | 41.8 | 110.2 | 158.3 |
|                    | T 18.3 | – | 71.6 | 104.5 |

* Calculated based on Chave et al. (2005) Wet forest for DBH > 10 cm.
is less than the mean minus one standard deviation \((1\sigma = 115 \text{ Mg ha}^{-1})\) and is in the 5th to 25th percentile reported by Spracklen and Righelato (2014). Compared to other Neotropical montane forests, AGB in Buenaventura and Tapichalaca is low both with respect to elevation (Fig. 2b) and slope angle (Fig. 2c).

Our estimates of AGB are less than some previous estimates of TMFs in the Ecuadorian Andes, for example 241 Mg ha\(^{-1}\) for 45 year old \textit{Alnus} forest; 366 Mg ha\(^{-1}\) for 30 year old \textit{Polylepis} forest at 3200–3600 m altitude (Fehse et al., 2002). However, values reported for plots in the Podocarpus National Park: 99 Mg ha\(^{-1}\) in similar mixed forest at 2380 m and 112 Mg ha\(^{-1}\) in elfin forest at 3060 m (Moser et al., 2011), were similar to the 104 Mg ha\(^{-1}\) that we measured for >40 year old forest at Tapichalaca, which is nearby. It is possible that low AGB at both sites is a legacy of historical selective logging. Selective logging would have resulted in the extraction of the largest trees, which are the largest contributor to AGB in mature forest (Berenguer et al., 2014). Analysis of the distribution of DBH at both sites demonstrates relatively few large stems (DBH > 50 cm) which may be an indication of past selective logging. The >40 year old forest plots we measure here store 36–58% less AGB compared to the mean AGB storage of 115 Mg ha\(^{-1}\) for 40 year old forest. These values include an estimate of the biomass in roots but do not include soil biomass or soil carbon, which is reported to exceed the total above ground carbon at a nearby site in southern Ecuador (Leuschner et al., 2013).

Fig. 3 shows above-ground biomass storage at both sites as a function of forest age. In Buenaventura, total AGB increased from 2.7 Mg ha\(^{-1}\) in recently abandoned pasture to 158 Mg ha\(^{-1}\) in >40 year old forest. In Tapichalaca, total AGB increased from 18.3 Mg ha\(^{-1}\) in recently abandoned pasture to 104 Mg ha\(^{-1}\) in >40 year old forest. A greater number of relict trees in the recently abandoned pasture at Tapichalaca resulted in AGB being greater than at Buenaventura.

At Buenaventura, total (above ground and roots) biomass storage increases from 3.6 Mg ha\(^{-1}\) in newly abandoned pasture to 185 Mg ha\(^{-1}\) in >40 year old forest. At Tapichalaca, total biomass increases from 22.3 Mg ha\(^{-1}\) in newly abandoned pasture to 119 Mg ha\(^{-1}\) in >40 year old forest. These values include an estimate of the biomass in roots but do not include soil biomass or soil carbon, which is reported to exceed the total above ground carbon at a nearby site in southern Ecuador (Leuschner et al., 2013).

Fig. 4 shows the calculated rate of AGB accumulation as a function of forest age. We calculate this rate as the difference in AGB storage between two forest sites divided by the difference in age between the two sites. We find that AGB accumulation is greatest in early stages of succession from pasture. In Buenaventura (1000 m a.s.l.), the rate of AGB accumulation is 9.8 Mg ha\(^{-1}\) yr\(^{-1}\) between 1 and 5 years, 9.8 Mg ha\(^{-1}\) yr\(^{-1}\) between 5 and 12 years, falling to no more than 1.7 Mg ha\(^{-1}\) yr\(^{-1}\) between 12 and >40 years. At Tapichalaca (2250 m a.s.l.), the rate averaged 4.1 Mg ha\(^{-1}\) yr\(^{-1}\) between 2 and 15 years and no more than 1.3 Mg ha\(^{-1}\) yr\(^{-1}\) between 15 and >40 years.

Fehse et al. (2002) calculated a time-averaged annual biomass accumulation (ABA) by dividing the AGB at a certain age by forest age for 17 Neotropical forest sites (this method includes the biomass present at time zero and so may overestimate net biomass accumulation). For ten young forest (4–8 year old) sites, the ABA averaged 11.8 (7.2–16.3) Mg ha\(^{-1}\) yr\(^{-1}\) falling to 8.3 (4.9–13.5) Mg ha\(^{-1}\) yr\(^{-1}\) for seven 15–20 year old sites. There was no significant difference between the lowland sites \((n=12)\) and montane sites \((n=4)\). Calculated in the same way, the ABA we observed were similar: 8.4 Mg ha\(^{-1}\) yr\(^{-1}\) at 5 years and 9.2 Mg ha\(^{-1}\) yr\(^{-1}\) at 12 years at Buenaventura, and 4.8 Mg ha\(^{-1}\) yr\(^{-1}\) at 15 years at Tapichalaca.


Rapid carbon accumulation in montane forests has been observed previously; Feulh et al. (2002) attributed rapid biomass accumulation to rapid sapling establishment and fast growth rate. Rapid regeneration of forests on disturbed sites has also been reported previously (Feulh et al., 2002; Scatena et al., 1996; Uhl and Jordan, 1984) but is dependant on site conditions and history (Knoke et al., 2014) and can be inhibited in sites that have been severely impacted by heavy grazing (Sarmiento, 1997). At the sites surveyed here, removal of grazing pressure was sufficient to allow sapling establishment and rapid accumulation of biomass.

To estimate the regional carbon sequestration by areas of abandoned pasture in southern Ecuador (Loja and Zamora Chinchipe Provinces) we combined information of the area of pasture in the region (1218 km²) from Tapia-Armijos et al. (2015), with an estimate of the fraction of pasture that has been abandoned (35%) from Knoke et al. (2014). This suggests that there is ~426 km² of abandoned pasture in the region. Combining this area with our estimate of biomass accumulation in areas of recently abandoned pasture (using the range of 4–10 Mg ha⁻¹ yr⁻¹) suggests a regional carbon sequestration of 85260–213 150 Mg C yr⁻¹ (assuming biomass is 50% carbon).

Fig. 5 shows the fraction of total biomass in different carbon pools as a function of forest age. Biomass stored in small trees (2.5 cm < DBH < 10 cm) made a considerable contribution to total carbon storage in young secondary forests (up to 50%) with a smaller contribution (<15%) in >40 year old forest. The importance of coarse woody debris (CWD) as a carbon store increased with forest age and with altitude, being 34% of total biomass storage for the >40 year old forest site at 2250 m elevation. Our estimates for the biomass stored in CWD in older secondary forests (25 and >40 year old forest site at 2250 m elevation) are consistent with Soethe et al. (2007), suggesting that we may under-predict root carbon biomass at the higher altitude sites.

4. Conclusion

We report on measurements of carbon storage in re-growing tropical montane forests in Ecuador. We analysed seven one hectare secondary montane forest plots in Southern Ecuador for above-ground biomass storage. The plots spanned a variety of forest ages from recently abandoned (1 year old) pasture to older secondary (at least 40 year old) forest. Older secondary forests were identified as areas where there was no visible sign of human disturbance or land slide activity and where there was no human disturbance within the last 40 years. Above-ground biomass storage in the >40 year old forest plots varied between 104 (at 2250 m elevation) and 158 Mg ha⁻¹ of land surface (at 1000 m elevation). On a planimetric area basis, above-ground biomass storage was 1.5% greater at 1000 m elevation and 10% greater at 2250 m elevation. The biomass storage reported here in >40 year old secondary forests is towards the lower end of that in previously studied tropical montane forests (Spracklen and Righelato, 2014). It is possible that historical selective logging occurred at both sites removing the largest trees and reducing the biomass values reported here. Above-ground biomass storage in recently abandoned (1–2 year old) pasture was 2–18 Mg ha⁻¹, with the larger value due to a greater number of relict trees that survived deforestation and pasture development. Biomass accumulation during the natural succession of pasture to secondary forest was rapid for the first 12–15 years being 10 Mg ha⁻¹ yr⁻¹ at 1000 m elevation and 4 Mg ha⁻¹ yr⁻¹ at 2250 m elevation. In our study natural regeneration was sufficient to establish secondary forest on areas on abandoned pasture, without the need for additional tree planting. Net biomass accumulation rates in our montane sites were similar to those observed previously in lowland humid tropical forests. The large areas of abandoned montane pasture in southern Ecuador (Knoke et al., 2014; Tapia-Armijos et al., 2015) means that reforestation and restoration of could sequester substantial amounts of carbon. Overall, our results suggest that reforestation and restoration of tropical montane forests should be considered as an important climate mitigation option.

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