

A METHOD FOR ESTIMATING THE CURRENT AND FUTURE CARBON CONTENT OF STANDING BIOMASS APPLIED TO GISHWATI FOREST RESERVE, RWANDA

D Courard-Hauri^{1,*}, R Chancellor², A Rundus³ & A Boland¹

¹Environmental Science and Policy Program, Drake University, Des Moines, IA, USA, 50311

²Departments of Anthropology & Sociology and Psychology, West Chester University, West Chester, PA 19383

³Department of Psychology, West Chester University, West Chester, PA 19383

*david.courard-hauri@drake.edu

Received June 2015

COURARD-HAURI D, CHANCELLOR R, RUNDUS A & BOLAND A. 2016. A method for estimating the current and future carbon content of standing biomass applied to Gishwati Forest Reserve, Rwanda. The carbon content of standing tree biomass was determined in the Gishwati Forest Reserve in north-western Rwanda and growth potential of the forest was estimated using a straightforward, generalisable model of natural forest regeneration. A survey was conducted on 2289 trees in plots throughout the reserve. Wood density data were obtained from literature and tree biomass was estimated using a recent pan-tropical allometric equation. A survey on United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM) projects showed that current methods of growth rate projection for mixed, non-plantation forests might significantly overestimate the amount of carbon sequestered. The current study identified an alternative potential method for the estimation of sequestration rates that did not depend upon compiling single-species growth rates and reduced the risk that error would lead to significant over- or underestimation of total biomass sequestration potential. This method used remote-sensing data to estimate total biomass potential in a mature forest based upon local samples and assumes a standard growth trajectory based upon literature values. The benefits in terms of accuracy and ease of model construction are likely to be high. It was found that tree biomass in Gishwati forest contained $53.9 \pm 10 \text{ CO}_2 \text{ equivalent(e) ha}^{-1}$ and was expected to sequester an average of $1.01 (0.80\text{--}1.38) \text{ Mg CO}_2\text{e ha}^{-1}$ per annum over the next 30 years.

Keywords: Carbon sequestration, REDD, forest growth rate, Albertine Rift

INTRODUCTION

The Gishwati forest in north-western Rwanda is a degraded montane forest fragment of roughly 10 km^2 that retains an important assemblage of biota, including the Eastern Chimpanzee (*Pan troglodytes schweinfurthii*), golden monkey (*Cercopithecus mitis kandti*) and other primates. The forest is part of the much larger Albertine Rift region, which includes approximately $313,000 \text{ km}^2$ of natural habitat from the eastern Democratic Republic of Congo to northern Zambia (Plumptre et al. 2003, 2007), and has been recognised as an area of conservation importance (Olson & Dinerstein 1998, Myers et al. 2000). Approximately 39% of all African mainland mammals can be found in this region (Plumptre et al. 2003), and the montane forest ecoregion within the Albertine Rift has been identified as one of the top three ecoregions in

the world with regard to number of endemic mammals (Olson et al. 2001). The Albertine Rift is also an area rich in plant species including at least 567 endemics, and the montane regions within this area have the largest number of threatened and endemic species such as *Brachystephanus roseus*, *Encephalartos whitelockii* and *Maesobotrya purseglovei* (Plumptre et al. 2003, IUCN 2015).

One of the most significant threats facing the entire Albertine Rift region, including its montane forests, is an increased demand for farmland and fuelwood (Plumptre et al. 2003). Rwanda, in turn, has one of the highest population densities in Africa, and most people rely on subsistence agriculture, an activity that has generated significant pressure on natural resources (Plumptre et al. 2001, 2004). Between

1958 and 1996, Rwanda lost 33% of its natural forests, including parts of montane regions such as Gishwati Forest Reserve (Plumptre et al. 2004). Deforestation at this scale not only affects biodiversity, but also generates other problems such as erosion. In Rwanda, erosion due to deforestation carries away an average of 11 Mg ha⁻¹ of soil every year (Waller 1996).

One potential conservation technique is the sale of credits for forest-based carbon sequestration in natural forest biomass, which provides valuable co-benefits in the form of biodiversity conservation, water purification, opportunities for tourism, protection of agricultural resources and more (Richards & Stokes 2004). Large-scale carbon sequestration in forests may be the single largest opportunity for low-cost carbon removal currently available, potentially removing nearly 7 gigatonnes of carbon dioxide equivalent (GtCO₂e) per year globally by 2030 at an approximate price of \$50 per tonne (McKinsey 2007).

Past carbon markets have been more robust than they are currently. The Clean Development Mechanism (CDM) of the Kyoto Protocol (Hunt 2009), allowed credit for active reforestation (regrowth of forests on land that did not contain it on 31 December, 1989) or afforestation (regrowth of forests on land that has been free of forests for 50 years). The CDM allowed countries or businesses to avoid legally mandated reductions, and as a result it had provided the highest per-carbon prices before the conclusion of the Kyoto Protocol in 2012, and its limited continuation into Phase II by the European Union, Switzerland and Australia. Due to surpluses in the market, the price per Mg of CO₂, called certified emission reductions, fell from a high range of USD 40 to under USD 0.5 by 2013 (ICE 2011).

Unlike the CDM, numerous certification organisations serving the voluntary market allow credit for reforestation, afforestation, or forest conservation (Kollmuss et al. 2008). These credits cannot be used to offset legally required carbon emissions, but they are commonly used for businesses and individuals to claim 'carbon neutrality' as they can purchase credits to offset emissions elsewhere in their operations. Even with the collapse of the mandatory markets, the voluntary market has remained robust with USD 379 million in offsets sold in 2013, and an

average price at about USD 5 (Peters-Stanley & Gonzales 2014).

Carbon mitigation through the regrowth and protection of largely natural forests has the potential for the greatest environmental benefits in terms of ecosystem services and biodiversity protection, while still providing significant long-term storage. However, quantification of sequestration potential through regrowth is not easy. Different tree species have very different growth rates and levels of mature biomass (Lieberman & Lieberman 1987). Thus, in calculating annual growth increments, CDM methodology calls for the use of species- or species group-specific data wherever possible (UNFCCC 2009). However, this produces a problem, i.e. species-specific growth data very often comes from timber plantations where conditions are manipulated to foster rapid growth. This leads to the potential for estimated growth rates to significantly exceed actual rates of growth in mixed forests, overestimating carbon sequestration in these cases.

It appears likely that this occurs in practice. A survey was carried out on each of the 32 afforestation/reforestation projects using CDM through 2011 (UNFCCC 2011). Six were projects that projected future benefits from the regrowth of mixed tropical forests, of which five estimated total biomass of woody vegetation at the end of the project cycle to be significantly greater than would be expected based upon forest type. Both of the African mixed forest projects estimated biomass significantly above estimates of local climax forest potential developed through remote sensing (Baccini et al. 2008). Remote sensing data provide an easily-accessible estimate for local forest biomass and biomass potential and thus have become common in biomass estimation work (Clark & Kellner 2012, Asner et al. 2012, Zolkos et al. 2013). Project 3206 estimated 303 Mg dry matter (dm) ha⁻¹ after 20 years of growth in wet montane forests, nearly twice more than Baccini et al. (2008). Project 2712 cited estimates of steady-state mature forest aboveground biomass to be 40 Mg (dm) ha⁻¹ in African tropical dry montane forests, and 191 Mg dm ha⁻¹ in African moist montane forests. Their site belonged mostly to tropical montane dry forests. However, the method of estimating annual increment independently led them to conclude that in

30 years the forest will contain 143.3 Mg dm ha⁻¹ of aboveground biomass, suggesting that the values were not even internally consistent within the project description.

These results raised the concern that a focus upon the estimation of annual increment, often from plantation data, led to an overestimation of the potential for sequestration from mixed forest projects. This study produced an estimate for carbon sequestration in woody biomass in the Gishwati forest that reduced the potential for under- or overestimation of total biomass sequestration potential.

MATERIALS AND METHODS

Study site

Gishwati Forest Reserve is a montane forest fragment in Albertine Rift, western Rwanda (1° 49' S, 29° 22' E), where montane forests are found between 1500 and 2500 m (Plumptre et al. 2007). Originally, part of an 800,000 ha (2 million acres) forest complex, the forest has recently fluctuated in size between 28,000 ha in 1970s and 600 ha in 2005. In 2007, it comprised 886 ha, referred to as 'core forest'. In 2008, 336 ha were added, and in 2009 a further 262 ha of a forest fragment called Kinyenkanda was incorporated. Gishwati thus currently includes about 1484 hectares of largely second-growth forest (GPFLR 2010). The core forest consists primarily of pioneer tree species such as *Dombeya torrida*, *Macaranga kilimandscharica* and *Maesa lanceolata*. The terrain is predominantly hilly (mean slope = 25.6°), but includes a large wet valley on the western side of the reserve. The elevation ranges from 2020–2500 m. A field station near the forest measured mean annual rainfall from 2010 through 2014 at 1893 mm, distributed seasonally with a major dry period between June and August. During the same period, the mean daily minimum and maximum temperature was 16.8 °C and 23.2 °C respectively. This study focused upon the original core forest.

Data collection

In 2010, data was collected on tree species diversity, stem density (trees ha⁻¹) and tree size. Trees under 10 cm diameter at breast height

(dbh) generally make up a very small fraction of total biomass, especially in paleotropical forests (Chidumayo 2002, Lewis et al. 2013). Therefore, the dbh and height were measured for all trees over 10 cm dbh within sixty 0.1 ha plots (Figure 1) along ten north–south parallel transects spaced at 400 m intervals across the core forest (mean transect distance: 2520 m, range: 1565–3450 m). Along these transect lines, plots were spaced at 500 m intervals and each plot was offset 10 m from the transect line. The team compiled a list of these parameters and species names for 2290 trees. Darbyshire of the Royal Botanic Gardens, Kew, E Fischer of the University Koblenz–Landau and his assistant Dumbo, helped to classify trees (Chancellor et al. 2012). The data was then used to estimate the carbon stock in standing woody biomass within the reserve.

Data analysis

Standing biomass

Pan-tropical allometric equations can produce estimates for the aboveground biomass (AGB) in a stand of trees to within 10% (with 95% certainty) if information is available on—in descending order of importance—dbh, wood density, height and rainfall (Chave et al. 2004). We used the pan-tropical allometric equation proposed by Chave et al. (2015) as no large-sample work has been done to produce local equations for forests in moist, montane regions of Africa:

$$AGB = 0.0509 \rho H D^2 \quad (1)$$

where ρ = wood density, H = height and D = diameter.

This equation appears to be quite robust for mixed-species tropical forests. We compared results in the Gishwati forest with the mean from five widely-used older allometric equations applicable to this region (Ponce-Hernandez 2004; Chave et al. 2004, Chave et al. 2005) and found a difference in total estimated aboveground biomass of less than 10%.

D and H were measured in the field (Chancellor et al. 2012). Where possible, ρ was taken from a detailed appendix in the UNFCCC's report on the Uganda Nile Basin Reforestation

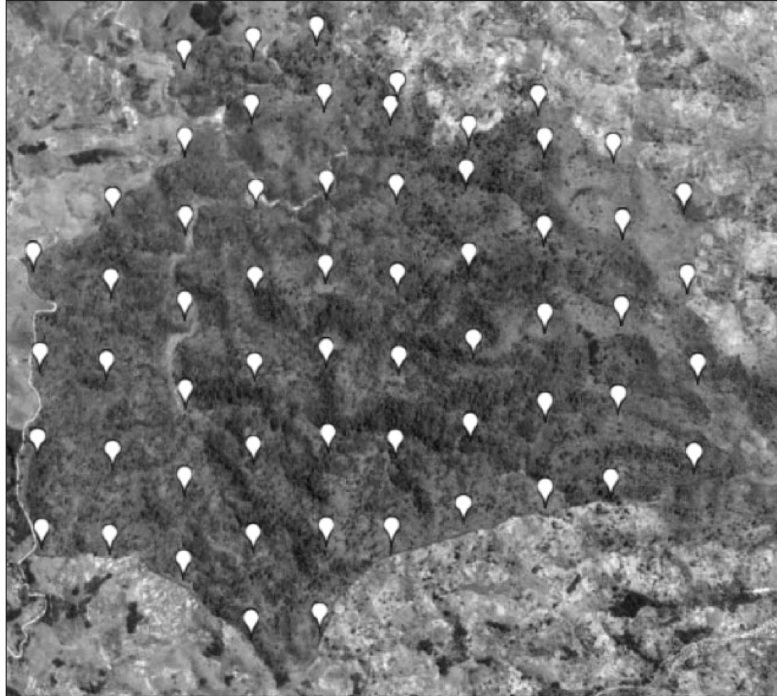


Figure 1 Plots in Gishwati forest. Each plot is 50 m × 20 m and all trees with dbh > 10 cm were measured within the plot; north is at the top of the figure

Project No. 3 (CDM 2009). This appendix includes density information for the majority of the species found in the Gishwati forest, using information from Eggeling (1940), Uganda Timbers and the Forest Research Office. In a few cases, no density information was available from the project report. The density was determined for *Acacia melanoxylon* (Prota 2011), *Alnus acuminata* (Moya and Muñoz 2010) and *Markhamia lutea* (Seebauer 2008). Muller-Landau (2004) found that the correlation between measured wood density and literature values was 0.82, suggesting a standard deviation of 10–15%. She also found that the wood density of multiple species responded to site-specific drivers, i.e. temperature, rainfall and elevation, in a similar way, meaning that wood density variation between species is not independent from site to site and errors may not cancel out.

Root biomass of trees is even more difficult to measure directly, but numerous studies have estimated its value based upon partial or full excavation of root systems. Cairns et al. (1997) performed a metastudy of literature estimates for root biomass at 62 sites and found that the aboveground biomass (AGB) explained

84% of the variation in belowground biomass (BGB) in trees. They produced the pan-tropical allometric equation for BGB:

$$\text{BGB} = 346.9(\text{AGB}/100)^{0.8836} \quad (2)$$

where BGB and AGB are both in units of kg per ha. Other potential allometric equations for African forests can be found in Shirima et al. (2011).

The AGB and BGB density per ha was calculated for forest edge and forest core. These two values were then weighted by the fraction of area each represented in order to determine the mean biomass density within the reserve.

To determine carbon content of the forest, the following equation was used:

$$C = kB \quad (3)$$

where C = carbon stock (Mg C ha⁻¹) and B = biomass. Depending upon the type of biomass involved, the conversion coefficient k commonly takes values between 0.45 and 0.6. The FAO directs researchers to use the value 0.55 for woody biomass in tropical forests, which is widely supported in literature (Ponce-Hernandez 2004).

This study provided an estimate for woody biomass within trees greater than 10 cm dbh, not including biomass in smaller trees, lianas or vascular plants. These were presumed to be a small fraction of the total biomass. It did not include biomass of leaf litter or dead biomass, as these stocks turn over rapidly and are also small. Finally, it did not include an estimate for the carbon stocks in soils. These are generally large and estimates for Rwandan soils are in the range of 50–100 Mg C ha⁻¹ (Henry 2010). However, turnover between the stock and the atmosphere is generally slow. As estimates for soil parameters in Gishwati were not available, no attempt was made to calculate the stock. Inclusion of the stock would be expected to increase the estimate of carbon sequestration in Gishwati forest because conversion of forest to agriculture does eventually lead to the loss of between a quarter and a half of the soil stock (Murty 2002, Henry 2010). Taking soil biomass into account, estimates for the loss of current biomass with conversion to agriculture could be increased by between 25 and 100%. However, narrowing that range is beyond the scope of this paper. Thus, the results only estimated a fraction of the total carbon kept from the atmosphere by protecting the Gishwati Forest Reserve.

Biomass accumulation

Gishwati is a mixed-species secondary forest composed of naturally propagated trees. Most of the information on African species-specific growth rates in the literature is from tree plantations. Plantation conditions are generally artificially optimised, with weed control, limiting light and nutrient competition from other species, tree spacing set for rapid growth, nutrient application and genetics selected for rapid biomass accumulation (Tiarks et al. 1998). Thus, these growth rates are unlikely to reflect growth in a competitive environment.

In a literature survey, Brown and Lugo (1990) collected information on biomass accumulation in secondary tropical moist and wet forests at various times during the first 80 years after the removal of all standing biomass. The authors, determining curve fit by eye, estimated total AGB and BGB stocks over time. They found a rapid initial growth rate slowing asymptotically

towards a maximum value, closely approximated with the functional form:

$$B = At/(t - d) \quad (4)$$

where B = biomass (Mg ha⁻¹), t = years since disturbance, A = asymptote (total biomass in a forest that has reached steady-state in terms of accumulation of woody vegetation) and d = a constant that determines the rapidity with which B approaches A. The instantaneous growth rate is then just the derivative of equation 4, with the growth in a given year equal to:

$$\frac{Ad}{t^2 + t(2Ad + 1) + d(A+d)} \quad (5)$$

which approaches zero as t gets larger.

This information can thus be used to estimate growth potential at any given future period for a natural forest. The asymptote A can be determined from values for climax forests in the region. If conditions (climate and expected A) are similar to those in Brown and Lugo (1990), their value for d can be used as well, though it can also be estimated locally if growth rates is determined over any known time period.

Using Maximum Likelihood Estimation (MLE), we calculated the best fit of equation 4 to the data points that Brown and Lugo (1990) provided in their work on tree growth in tropical forests (Figure 2). The best fit curve for AGB closely approximated the curve drawn by the authors, though the initial growth rate was estimated to be slightly smaller. Due to a large amount of uncertainty in the BGB values, it was assumed to be 21% of AGB at any point in time (equation 2). This approximation also followed the hand-drawn curve that Brown and Lugo (1990) produced.

The asymptote for mature forest was calculated from Brown and Lugo (1990) at 162.9 Mg ha⁻¹. Baccini et al. (2008) used satellite imaging to obtain information on mature, mixed species tropical forests and found a value for AGB in central African montane forest of 169.3 Mg ha⁻¹. Since the value that Baccini obtained was specific to the type of forest that Gishwati will become, the equation obtained from Brown and Lugo (1990) was adjusted using 169.3 for A, rather than 162.9. This retained the

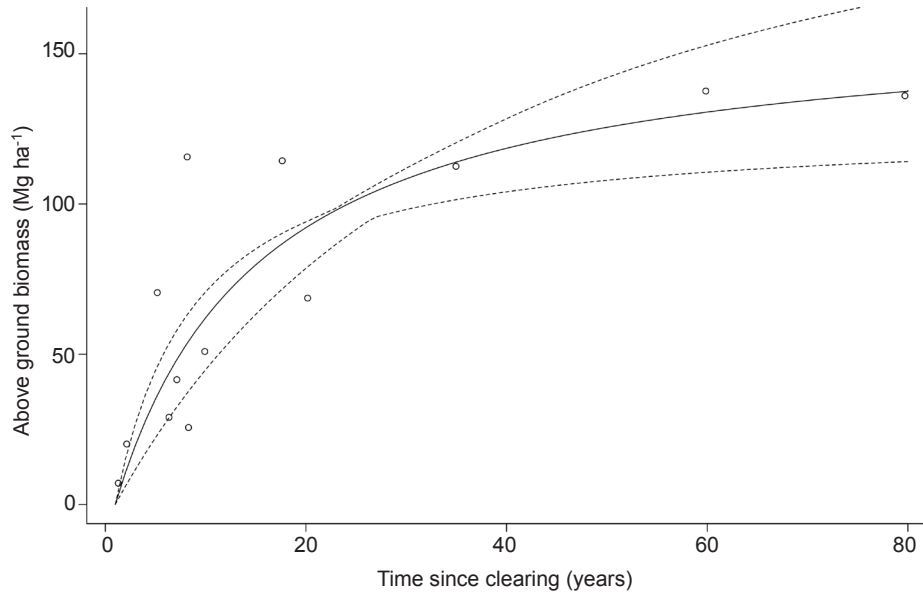


Figure 2 Growth rates of tropical forests (Brown and Lugo, 1990); points (·) = values from the literature, solid line (—) = best-fit value using maximum likelihood estimation and dashed line (---) = 90% confidence limits

shape of the growth curve but substitutes a more accurate asymptote:

$$AGB = 169.3t / (t + 14.6) \tag{6}$$

Carbon in standing biomass at any point in time was estimated using the equation:

$$C = 1.21 \times 0.55 \times 169.3 \times t / (t + 14.6) \tag{7}$$

$$= 0.6655 \times 169.3 \times t / (t + 14.6)$$

where 1.21 adjusted for BGB and 0.55 converted Mg of biomass to Mg of carbon. The growth rate at any point in time was:

$$\frac{dC}{dt} = \frac{169.3 \cdot 14.6}{t^2 + 2 \cdot 14.6t + 14.6^2} = \frac{1645}{t^2 + 29.2t + 213.2} \tag{8}$$

The value of *t* was the time since the forest began to fully regenerate, without disturbance. History similar to that of Gishwati is common, however: forests may not ever be fully cleared, disturbances are partial, and *t* is area-specific. Thus, the ‘effective age’ of the forest was estimated by substituting a measured value of standing biomass for *B* in equation 6 and solving for *t* to obtain a value usable in modeling.

RESULTS

Standing biomass

Two species, *Symphonia globulifera* and *Myrianthus holstii* made up nearly 34% of the total woody biomass, due mostly to the presence of numerous large trees. The top ten species accounted for over 75% of total woody biomass (Table 1).

Figure 3 shows the measurements of sample from forest edge. The forest edge region contained 22 of the 60 plots (37%), but included only 16.5% of the total forest area. Forest edge had lower average biomass than forest core, most likely due to historical use by people in surrounding communities and the limited regeneration time since 2005, when the forest reached its smallest size. To correct for bias, the samples were separated into two regions; forest edge was defined as the region within 110 m of the forest boundary and forest core was the remaining forest.

It was calculated that the forest core contained $102.4 \pm 19 \text{ Mg ha}^{-1}$ of biomass (84.9 Mg ha^{-1} in AGB, 17.6 in BGB), while forest edge contained $75.0 \text{ Mg ha}^{-1} \pm 14$ (61.7 Mg ha^{-1} in AGB and 13.3 Mg ha^{-1} in BGB). This amount of biomass represented

Table 1 Number of trees, biomass and their diameter at breast height (dbh) values for selected tree species with highest biomass in Gishwati forest, Rwanda

Species	Fraction of total biomass	Number of trees in sample	Largest dbh (cm)	Median dbh (cm)
<i>Symphonia globulifera</i>	0.220	27	122.0	51.0
<i>Myrianthus holstii</i>	0.118	89	100.0	27.4
<i>Strombosia scheffleri</i>	0.088	53	88.5	33.5
<i>Dombeya goetzenii</i>	0.074	382	59.4	13.0
<i>Macaranga kilimandscharica</i>	0.060	302	85.5	14.2
<i>Maesa lanceolata</i>	0.056	351	70.3	13.4
<i>Carapa grandiflora</i>	0.049	50	68.6	20.1
<i>Polyscias fulva</i>	0.038	67	90.2	13.7
<i>Chrysophyllum gorungosanum</i>	0.037	10	92.0	38.3
<i>Acacia melanoxylon</i>	0.037	178	27.6	14.4

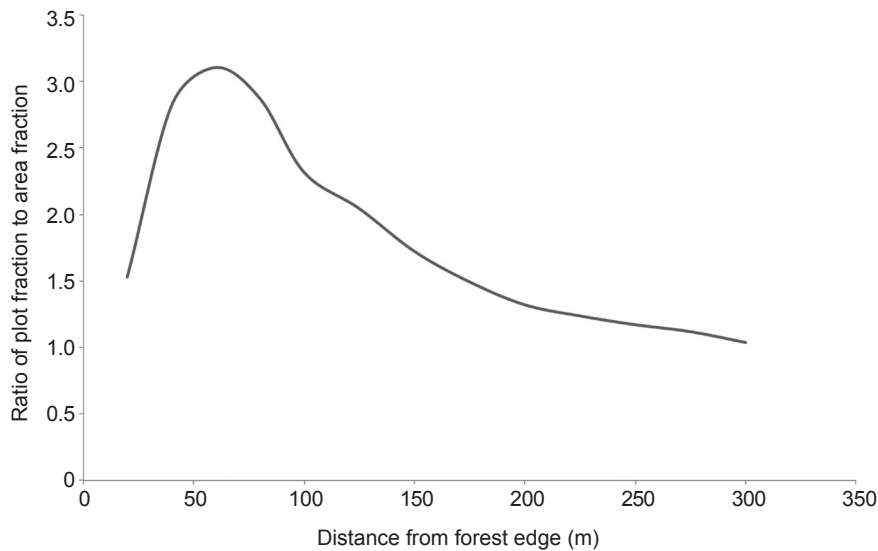


Figure 3 The fraction of plot points divided by the fraction of forested area within Gishwati as one moves inward from the forest edge

53.9 ± 10 Mg C ha⁻¹ throughout the forest, or 47,700 Mg C ± 9,000 (175,000 Mg CO₂ emission(e)) total within the 886 ha of the park.

Expected growth

With 53.9 Mg C ha⁻¹ of biomass, equation 7 was used to calculate an effective age of 13.4 years. This did not represent the actual age since clearing, as Gishwati contained a few very large trees as well as areas that had been cleared quite recently. Also, different regions in the

forest had been disturbed at different times and in some places the disturbance had only been partial, for example, with the selective removal of small trees. However, finding the effective age allowed estimation of expected growth rates as the forest ages and moves toward maturity.

Using 13.4 as the current time, carbon sequestration was estimated at various time points in the future (Table 2). It was estimated that over the next 30 years, Gishwati forest will sequester 1.01 (0.80–1.38) Mg C ha⁻¹ per year (3.7 Mg CO₂e ha⁻¹).

Table 2 Expected carbon sequestration rates

Years from present	Instantaneous sequestration rate t ha ⁻¹	Mean sequestration rate Mg C ha ⁻¹ yr ⁻¹
1	1.96	2.03 (1.75, 2.29)
5	1.51	1.78 (1.51, 2.10)
7	1.34	1.68 (1.41, 2.02)
10	1.14	1.57 (1.28, 1.90)
30	0.49	1.01 (0.80, 1.38)

The instantaneous rate represents the derivative of the curve (equation 11), and is lower than the average rate due to exponential decay over time, mean sequestration rate represents expected annual sequestration over the period from the measurement date to the time indicated, (90% confidence intervals in parentheses)

DISCUSSION AND CONCLUSIONS

The study presented a two-step process for estimating the sequestration potential of degraded natural forest. The method was more accurate and generalisable than the currently accepted practice and could be used in forests such as Gishwati that had undergone partial harvesting. This method requires the construction of an annual increment curve, but it is more critical to correctly estimate the expected steady-state value than the increment in any given year. This is because much of the forest biomass is likely to accumulate during the project lifetime and a misestimate of the steady-state value can lead to a significant error in the prediction of total carbon accumulated.

Unless the forest has been clearcut, the first step is to estimate the standing biomass using either a local or general allometric equation. Error from allometry combined with sampling error as well as uncertainties related to wood density and BGB, is generally within established tolerance. A determination of the standing biomass then places the forest at a unique point on the growth curve, from which growth increments may be calculated for future years.

The second step is thus to estimate the future growth potential of the forest. The most important step here is determining a reasonable maximum value, at which a forest will reach rough steady-state. This is perhaps the least well-quantified number in most mixed forest models, and it appears that current models based upon single-species growth curves are not performing well in this category. Remote sensing technology has improved, and where possible,

its value should be used to parameterise growth models rather than emerge from single-species calculations. Taken together, errors in the first step (measurement of biomass) are mitigated by the second step in the model. Large estimates for standing biomass lead to lower expected growth rates and vice versa.

The most important shortcomings of the method of estimation are: (1) it is based upon an estimate of growth rates for tropical forests in general, rather than for the specific conditions of Gishwati Forest (although the asymptote specific to forests similar to Gishwati), (2) it is not based upon species-specific growth rates, although the particular composition of the forest may lead to varying growth rates for the forest as a whole if it differs significantly from a typical forest and (3) it does not take into account the effects of shading from individual large trees that exist in Gishwati. Of these, the last is the most problematic and the most difficult to account for without an actual spatial model of the forest. However, the use of data from actual forests rather than plantations mitigates this concern somewhat. Moreover, a small degree of shelterwood has been shown to enhance forest growth over that in a clearcut environment (Paquette et al. 2006), so there is the potential for our values to underestimate short-term sequestration potential in Gishwati.

An assessment of the generalisability of this method is beyond the scope of the current paper, as it requires a large data set of natural forest growth estimates over a period of decades. Such a data set was not available, although it was intended to monitor the growth rate of the Gishwati forest over time. Future research will

resolve whether the methodology presented here provided reasonable short-term carbon sequestration estimates.

Gishwati forest currently contained about 175,000 Mg CO₂e in trees over 10 cm dbh. On the open voluntary market, this is worth about USD 875,000. The annual sequestration rate over the next 30 years is about 3.7 Mg CO₂e ha⁻¹, adding over USD 16,000 in annual new sequestration benefits over the park as a whole. Thus, even at a very low carbon valuation, the climate benefits add a significant amount to the already important conservation value of the forest.

ACKNOWLEDGEMENTS

The authors would like to thank S Nyandwi, T Safari, S Uwimana, P Mwiseneza, A Ndayambaje, I Ngayincyuro, O Ngabonziza and E Munyeshuli, all of whom were part of the team that produced the tree measurement data. We would also like to thank B Beck, scientist emeritus at the Smithsonian Conservation Biology Institute, for many helpful discussions and suggestions. We thank the Great Ape Trust of Central Iowa for financial support of parts of this research.

REFERENCES

- ASNER GP, MASCARO J, MULLER-LANDAU HC, VIELLEDENT G, VAUDRY R, RASAMOELINA M, HALL JS & VAN-BREUGEL M. 2012. A universal airborne LiDAR approach for tropical forest carbon mapping. *Ecosystem Ecology* 128:1147–1160.
- BACCINI A, LAPORTE N, GOETZ J, SUN M & DONG H. 2008. A first map of tropical Africa's above-ground biomass derived from satellite imagery. *Environmental Research Letters* 3: 1–9.
- BROWN S & LUGO A. 1990. Tropical secondary forests. *Journal of Tropical Ecology* 6: 1–32.
- CAIRNS M, BROWN S, HELMER EH & BAUMGARDNER GA. 1997. Root biomass allocation in the world's upland forests. *Oecologia* 111: 1–11.
- CDM (CLEAN DEVELOPMENT MECHANISM). 2009. *Project 1578: Uganda Nile Basin Reforestation Project No. 3, Appendix 7*. Technical report. United Nations Framework Convention Climate Change, New York.
- CHANCELLOR R, RUNDUS A & NYANDWI S. 2012. The influence of seasonal variation on chimpanzee (*Pan troglodytes schweinfurthii*) fallback food consumption, nest group size and habitat use in Gishwati, a montane rainforest fragment in Rwanda. *International Journal of Primatology* 33: 115–133.
- CHAVE J, CONDIT R, AGUILAR S, HERNANDEZ A, LAO S & PEREZ R. 2004. Error propagation and scaling for tropical forest biomass estimates. *Philosophical Transactions of the Royal Society of London, B* 359: 409–420.
- CHAVE J, ANDALO C, BROWN S ET AL. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145: 87–99.
- CHAVE J, RÉJOU-MÉCHAIN M, BÚRQUZ A ET AL. 2015. Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology* 20: 3177–3190.
- CHIDUMAYO EN. 2002. Changes in miombo woodland structure under different land tenure and use systems in central Zambia. *Journal of Biogeography* 29: 1619–1626.
- CLARK DB & KELLNER JR. 2012. Tropical forest biomass estimation and the fallacy of misplaced concreteness. *Journal of Vegetation Science* 23:1191–1196.
- EGGELING W. 1940. The indigenous trees of Uganda. PhD thesis, University of Edinburgh, Edinburgh.
- GPFLR (GLOBAL PARTNERSHIP ON FOREST LANDSCAPE REFORESTATION). 2010. *Global Partnership on Forest Landscape Reforestation, Gishwati Area Conservation Program*. <http://www.forestlandscaperestoration.org/learning-site-gishwati/>
- HENRY M. 2010. C Stocks and dynamics in Sub-Saharan Africa. PhD thesis, University of Tuscia, Viterbo.
- HUNT CA. 2009. *Carbon Sinks and Climate Change: Forests in the Fight Against Global Warming*. Edward Elgar Publishing, Northampton.
- ICE (INTER CONTINENTAL EXCHANGE). 2011. *Inter Continental Exchange Exx Cer Futures*. <https://www.theice.com/productguide/ProductDetails.shtml?specId=814666>
- IUCN (INTERNATIONAL UNION FOR CONSERVATION OF NATURE). 2015. *The IUCN Red List of Threatened Species. Version 2015–3*. <http://www.iucnredlist.org>.
- KOLLMUSS A, ZINK H & POLYCARP C. 2008. *Making Sense of the Voluntary Carbon Market: A Comparison of Carbon Offset Standards*. Wildlife Fund, WWF, Stockholm.
- LEWIS SL, SONKÉ B, SUNDERLAND T ET AL. 2013. Above-ground biomass and structure of 260 African tropical forests. *Philosophical Transactions of the Royal Society of London B* 368: 20120295.
- LIEBERMAN D & LIEBERMAN M. 1987. Forest tree growth and dynamics at La Selva, Costa Rica (1969-1982). *Journal of Tropical Ecology* 3: 347–358.
- MCKINSEY. 2007. *A Cost Curve for Greenhouse Gas Reduction*. McKinsey and Company, New York.
- MOYA R & MUNOZ F. 2010. Physical and mechanical properties of eight fast-growing plantation species in Costa Rica. *Journal of Tropical Forest Science* 22: 317–328.
- MULLER-LANDAU HC. 2004. Interspecific and inter-site variation in wood specific gravity of tropical trees. *Biotropica* 36: 20–32.
- MURTY D, KIRSCHBAUM MUF, MCMURTRIE RE & MCGILVRAY H. 2002. Does conversion of forest to agriculture land change soil carbon and nitrogen? A review of the literature. *Global Change Biology* 8: 105–123.
- MYERS N, MITTERMEIER R, MITTERMEIER C, DA FONSECA G &

- KENT J. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403: 853–858.
- OLSON D & DINERSTEIN E. 1998. The global 200: a representation approach to conserving the earth's most biologically valuable ecoregions. *Conservation Biology* 12: 502–515.
- OLSON D, DINERSTEIN E, WIKRAMANAYAKE E ET AL. 2001. Terrestrial ecoregions of the world: a new map of life on Earth. *Bioscience* 51: 933–938.
- PAQUETTE A, BOUCHARD A & COGLIASTRO A. 2006. Survival and growth of under-planted trees: A meta-analysis across four biomes. *Ecological Applications* 16: 1575–1589.
- PETERS-STANLEY M & GONZALES G. 2014. *Sharing the Stage: State of the voluntary carbon markets 2014*. Ecosystem Marketplace and Bloomberg New Energy Finance, New York.
- PLUMPTRE A, BEHANGANA M, NDOMBA E ET AL. 2003. *The Biodiversity of the Albertine Rift*. Albertine Rift Technical Reports No. 3. Wildlife Conservation Society, New York.
- PLUMPTRE A, DAVENPORT T, BEHANGANA M ET AL. 2007. The biodiversity of the Albertine rift. *Biological Conservation* 134: 178–194.
- PLUMPTRE A, KAYITARE A, RAINER H ET AL. 2004. *The Socio-Economic Status of People Living Near Protected Areas in the Central Albertine Rift*. Albertine Rift Technical Reports No. 4. Wildlife Conservation Society, New York.
- PLUMPTRE A, MASOZERA M & VEDDER A. 2001. *The Impact of Civil War on the Conservation of Protected Areas in Rwanda*. World Wildlife Fund, Washington DC.
- PONCE-HERNANDEZ R. 2004. *Assessing Carbon Stocks and Modelling Win-Win Scenarios of Carbon Sequestration Through Land-Use Changes*. Food and Agriculture Organization of the United Nations, Rome.
- PROTA. 2011. Prota database, *Acacia melanoxylon*. <http://database.prota.org/PROTAhtml/Acacia>
- RICHARDS KR & STOKES C. 2004. A review of forest carbon sequestration cost studies: A dozen years of research. *Climate Change* 63: 1–2.
- SEEBAUER M. 2008. Silvicultural study on *Markamia lutea* with regard to short energy plantations. <http://www.ceg.ncl.ac.uk/>
- SHIRIMA DD, MUNISHI PKT, LEWIS SL ET AL. 2011. Carbon storage, structure and composition of miombo woodlands in Tanzania's eastern arc mountains. *African Journal of Ecology* 49: 332–342.
- TIARKS A, NAMBIAR EKS & COSSALTER C. 1998. *Site Management and Productivity in Tropical Forest Plantations*. Center for International Forestry Research, Bogor.
- UNFCCC (UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE). 2009. *Simplified Baseline and Monitoring Methodology for Small-Scale Agroforestry-Afforestation and Reforestation Project Activities under the Clean Development Mechanism, Version 2.0*. Technical report. UNFCCC, New York.
- UNFCCC (UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE). 2011. Project cycle search page: Afforestation and reforestation. <http://cdm.unfccc.int/Projects/projsearch.html>
- WALLER D. 1996. *Rwanda: Which Way Now? An Oxfam Country Profile*. Oxfam, Oxford.
- ZOLKOS SG, GOETZ SJ & DUMBAYAH R. 2013. A meta-analysis of terrestrial aboveground biomass estimation using LiDAR remote sensing. *Remote Sensing of Environment* 128: 289–298.