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Measuring, monitoring, and verification of carbon benefits for forest-based projects

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Worldwide, there are many pilot forestry projects that are under some stage of implementation, and much experience has been gained from them with respect to measuring, monitoring, and accounting for their carbon benefits. Forestry projects have been shown to be easier to quantify and monitor than national inventories, partly because not all pools need measuring: a selective accounting system can be used that must include all pools expected to decrease and a choice of pools expected to increase as a result of the project. Only pools that are based on field measurements should be incorporated into the calculation of carbon benefits. Such a system allows for trade-offs between expected carbon benefits, costs, and desired precision, while maintaining the integrity of the net carbon benefits. Techniques and methods for accurately and precisely measuring individual carbon pools in forestry projects exist, are based on peer reviewed principles of forest inventory, soil sampling, and ecological surveys, and have been well tested in many part of the world. Experience with several forestry projects in tropical countries has shown that with the use of these techniques carbon stocks can readily be estimated to be within less than ±10% of the mean. To date, there is little experience with measuring the changes in carbon stocks over time but, using the correct design and sufficient numbers of permanent plots, it is expected that precision levels will be maintained at less than ±10% of the mean. Internal verification can be accomplished through use of quality assurance/quality control plans. External or third-party verification is still in its infancy, and would greatly benefit from international agreements in relation to protocols used for all aspects of project design and implementation.

Keywords: carbon credits; tropical forests; root biomass; project monitoring; carbon pools; accreditation

1. Introduction

Many forest-based projects have been developed and are currently under various stages of implementation. Much experience has been gained from these projects with respect to measuring, monitoring, and accounting for the carbon benefits derived

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from them. Focusing on carbon simplifies project development because the problem is reduced to calculating the net differences between carbon stocks for the 'with-project' and the 'without-project' conditions (also referred to as the business-as-usual baseline) on the same piece of land over a specified time period. The challenge is to identify which carbon stocks need to be quantified in the project, to measure them accurately to a known, and often predetermined, level of precision, and to monitor them over the length of the project.

The focus of this paper is on measuring, monitoring, and verifying the carbon benefits from the implementation of forest-based projects. The main goals are to:

(i) describe criteria and approaches for selecting which carbon pools to measure;

(ii) describe the tools and techniques commonly available to measure and monitor these pools;

(iii) illustrate how these tools have been applied to existing pilot projects;

(iv) discuss other relevant measuring and monitoring issues; and

(v) discuss the need for project verification.

2. Which carbon pools to measure?

Land use and forestry projects are generally easier to quantify and monitor than national inventories, due to clearly defined boundaries for project activities, relative ease of stratification of project area, and choice of carbon pools to measure (Brown *et al.* 2000*b*). Criteria affecting the selection of carbon pools to inventory and monitor are: type of project; size of the pool, its rate of change, and its direction of change; availability of appropriate methods; cost to measure; and attainable accuracy and precision (MacDicken 1997*a*, *b*). The carbon credits from a project for all pools measured (pools 1 to n) are given by

$$\sum_{1}^{n} (\text{C in pool}_1 \text{ for with-project case} - \text{C in pool}_1 \text{ for without-project case}),$$

where the carbon pool is the product of the area of a given land use and the carbon density (carbon per unit area).

It is clear that for some carbon pools the difference will be positive, e.g. stopping deforestation or lengthening forest rotation will lead to more carbon in trees on average (with-project) than conversion of forests to agriculture or shorter rotation (without-project). For other pools, the difference could be negative, e.g. the dead-wood pool in a reduced impact logging project will be less than the dead-wood pool in a conventional logging practice. Basically, a selective or partial accounting system can be used that must include all pools expected to decrease (i.e. those pools that are smaller in the with-project case than in the without-project case) and a choice of pools expected to increase (i.e. those pools that are larger in the with-project case than in the without-project case) as a result of the project (Brown *et al.* 2000*b*). Only pools that are measured (or estimated from a measured parameter) and monitored are incorporated into the calculation of carbon benefits.

Table 1. *A decision matrix of the main carbon pools for examples of forestry projects*

(This table illustrates the selection of pools to quantify and monitor (based on Brown *et al.* (2000*b*)). Y, yes: indicates that the change in this pool is likely to be large and should be measured. R, recommended: indicates that the change in the pool could be significant but measuring costs to achieve desired levels of precision could be high. N, no: indicates that the change is likely to be small to none and thus it is not necessary to measure this pool. M, maybe: indicates that the change in this pool may need to be measured, depending upon the forest type and/or management intensity of the project.)

	carbon pools						
	live biomass			dead biomass			
project type	trees	herbaceous	roots	fine	coarse	soil	wood products
avoid emissions							
stop deforestation	Y	M	R	M	Y	R	M
improved forest management	Y	M	R	M	Y	M	M
sequester carbon							
restore native forests	Y	M	R	Y	Y	M	N
plantations	Y	N	R	M	M	R	Y
agroforestry	Y	Y	M	N	N	R	M

The major carbon pools in forestry projects are live biomass, dead biomass, soil, and wood products (table 1). These can be further subdivided as needed, e.g. live biomass includes aboveground trees, roots, and understorey, and dead biomass can include fine litter, lying dead wood, and standing dead trees. Decisions about which pools to chose for measuring and monitoring for different types of forestry projects are also illustrated in table 1. Carbon in trees should be measured for practically all of these project types as this is where most of the carbon benefits will be derived from; measurement of carbon in the understorey is recommended in cases where this is a significant component, such as in agroforests or open woodlands; dead wood should be measured in all forest-based projects, as this can be a significant pool of carbon, and must be measured in projects related to stopping or changing harvesting practices. Land-use change and forestry projects have often been targeted for criticism because it has been suggested that changes in soil-carbon pools are difficult to measure. However, for most forestry projects, soil need not be measured if it can be shown that the project will not result in a loss of soil carbon. Most projects related to forests, whether they be protection of threatened forests, improved management for timber harvest, forest restoration, or longer rotation plantations, will not cause soil carbon to be lost and, if anything, will cause carbon in soil to be maintained or increase.

The decision matrix presented in table 1 implies that one design does not fit all projects, i.e. measuring and monitoring designs will vary by project type and the resources available to make the measurements. Regardless of the fact that one design does not fit all types of projects, the specific methods used to measure any given pool should give accurate and precise results, be based on peer-reviewed and tested methods, and be cost and time efficient.

3. Tools and techniques available for measuring carbon in forest-based projects

Before implementing a carbon project, experience with pilot projects has shown that an assessment of the area, including collecting as much relevant data as possible, is a time- and cost-efficient activity. Relevant information includes: a land-cover/land-use map of the project area; identification of pressures on the land and its resources; history of land use in the project area; the climate regime (particularly temperature and rainfall); soil types, topography and socio-economic activities (e.g. forestry and agricultural practices). Such information is useful to delineate relatively homogeneous forest strata (e.g. by forest type, soil type, topography, land use, etc.) for designing the measuring and monitoring sampling scheme, improving baseline projections, and developing guidelines for leakage avoidance. Preliminary sampling of the identified strata is also needed to determine their variability in carbon stocks. This information is then used to determine the number of plots needed in each stratum to achieve desired precision levels based on sampling error.

Techniques and methods for sampling design and for accurately and precisely measuring individual carbon pools in forestry projects exist and are based on commonly accepted principles of forest inventory, soil sampling, and ecological surveys (Pinard & Putz 1996, 1997; MacDicken 1997*a*, *b*; Post *et al*. 1999; Winrock International 1999; Brown *et al*. 2000*a*; Hamburg 2000). For making an inventory of forest carbon, the use of fixed-area permanent plots (using a series of nested plots for uneven-aged and a single plot for even-aged forests) and tagging all trees is recommended; this approach is generally considered to be the statistically superior means for evaluating changes in forest-carbon pools. Within these plots, all the carbon pools can be measured or estimated, with the exception of wood products. Methods are well established and tested for determining the number, size, and distribution of permanent plots (i.e. sampling design) for maximizing the precision for a given monitoring cost (MacDicken 1997*a*).

To estimate live tree biomass, diameters of all trees are measured and converted to biomass and carbon estimates (carbon equals 50% of biomass), generally using allometric biomass regression equations. Such equations exist for practically all forests of the world; some are species specific and others are more generic in nature (see, for example, Alves *et al*. 1997; Brown 1997; Schroeder *et al*. 1997; Chambers *et al*. 2001; Keller *et al*. 2001). Sampling a sufficient number of trees to represent the size and species distribution in a forest to generate local allometric regression equations with high precision, particularly in complex tropical forests, is extremely time-consuming and costly, and generally beyond the means of most projects. From field experience, it has been shown that grouping all species, even in species-rich tropical forests, produces regression equations with high r^2 (generally greater than 0.95).

Experience to date with the development of generic regression equations, for both tropical and temperate forests, has shown that measurements of diameter at breast height, as is typical for trees, explains more than 95% of the variation in tree biomass even in highly species rich tropical forests. Thus the need to develop species-specific equations is not warranted (see, for example, Brown 1997; Chambers *et al*. 2001; Keller *et al*. 2001). However, in many forests, particularly in the tropics, unique plant forms occur such as species of palms and early colonizers. In these cases it is recommended that local regression equations be developed (in two pilot projects in the tropics, local regression equations were developed for *Cecropia* spp. (early colonizers) and several species of palms (Delaney *et al*. 2000; S. Brown & M. Delaney 2001, unpublished report)). For palms, we have found that height is the key independent variable for explaining variations in biomass, rather than diameter-at-breast-height (DBH).

The advantage of using generic regression equations, stratified by, for example, ecological zones or species group (broadleaf or conifer), is that they tend to be based on a large number of trees (Brown 1997) and span a wider range of diameters; this increases the accuracy and precision of the equations. It is very important that the database for regressions equations contains large diameter trees, as these tend to account for more than 30% of the aboveground biomass in mature tropical forests (Brown & Lugo 1992; Pinard & Putz 1996). A disadvantage is that the generic equations may not accurately reflect the true biomass of the trees in the project. However, field measurements, e.g. diameter and height relationships of the larger trees, or destructive harvest of two or three representative large trees performed at the beginning of a project, can be used to check the validity of the generic equations. For plantation projects, developing or acquiring local biomass regression equations is less problematic, as much work has been done on plantation species (Lugo 1997).

Dead wood, both lying and standing, is an important carbon pool in forests and one that should be measured in many forestry projects (table 1). Dead wood is generally divided into coarse and fine, with the breakpoint set at 10 cm diameter (Harmon & Sexton 1996). Although coarse dead wood, including standing and lying, is often a significant component of forest ecosystems, often accounting for 10–20% of the aboveground biomass in mature forests (e.g. Harmon *et al*. 1993; Delaney *et al*. 1998), it tends to be ignored in many forest-carbon budgets. Methods have been developed for this component and have been tested in many forest types and generally require no more effort than measuring live trees (Harmon & Sexton 1996; Brown 2002).

Total root biomass is another important carbon pool and can represent up to 40% of total biomass (Cairns *et al*. 1997). However, quantifying this pool can be expensive and no practical standard field techniques yet exist (Körner 1994; Kurz *et al*. 1996; Cairns *et al*. 1997). A recent literature review by Cairns *et al*. (1997) included more than 160 studies covering tropical, temperate, and boreal forests that reported both root biomass and aboveground biomass. The mean root-to-shoot ratio (R/S) based on these studies was 0.26, with a range of 0.18 (lower 25% quartile) to 0.30 (upper 75% quartile). The R/S did not vary significantly with latitudinal zone (tropical, temperate and boreal), soil texture (fine, medium and coarse), or tree type (angiosperm and gymnosperm). Further analyses of the data produced a significant regression equation of root biomass density versus aboveground biomass density when all data were pooled (r^2 of 0.83). Such a regression equation is useful for estimating root biomass from aboveground biomass in a cost-efficient way.

The ability to measure soil-carbon pools is a source of contention in forestry projects as mentioned above; however, as for vegetation, there is a well established set of methods and documentation for measuring soil-carbon pools (Post *et al*. 1999). Measuring change in soil carbon over relatively short time periods is more problematic but, as shown in table 1, this pool need not be measured in most projects. In cases where changes in soil carbon are included, rates of soil oxidation under different land uses are available in the literature (e.g. those summarized in the land-use and forestry sector of the *IPCC guidelines for national greenhouse gas inventories*; Houghton *et al*. 1997).

The long-term effectiveness of carbon storage in wood products depends on the uses of wood produced through project activities. In projects that reduce output of harvested wood by preventing logging or by improved forest management (and deforestation if some of the wood cut during deforestation entered the wood-products market), the change in the wood-products pool would be negative because the production for the with-project case would be less than for the without-project case. This negative change in the wood-product pool would reduce some of the carbon benefits from the project and this would have to be accounted for. In plantation projects, wood that goes into long- to medium-term products (e.g. sawtimber for housing, particle board, paper) represents an additional carbon storage. Several methods exist for accounting for the storage of long-lived wood products (Winjum *et al*. 1998). Recently, an IPCC Expert group for the Land Use and Forestry sector of the Guidelines for GHG inventories (Houghton *et al*. 1997) completed a report that describes and evaluates the approaches available for estimating carbon emissions or removals for forest harvesting and wood products (Brown *et al*. 1999; Lim *et al*. 1999).

4. Tools and techniques for ongoing project monitoring

Monitoring relates to the ongoing measurement of carbon pools and for compliance of the project's activities. For ongoing carbon monitoring, permanent sample plots are generally considered as the statistically superior and cost- and time-efficient means for evaluating changes in carbon stocks (MacDicken 1997*a*). Not all of the initial carbon pools need be measured at every interval in some projects; the judicious selection of some pools could serve as indicators that the project is following the expected trajectory. The frequency and intensity of monitoring depends to a large extent on the nature of the project. Those projects designed to avoid emissions through averting deforestation or logging need primarily to establish that no trees are removed or clearings made over the course of the project (monitoring for compliance) and that the amount of carbon is remaining constant or increasing (monitoring for carbon). In projects designed to sequester carbon, e.g. in forest restoration or through establishment of new forests, changes in all carbon stocks being claimed need to be remeasured periodically. This can be readily accomplished by the remeasurement of marked trees in permanent plots and remeasuring the other components with the methods described above.

Remote-sensing technology may be useful for monitoring forestry projects, although to date it has hardly been used. Interpretation of satellite imagery has been used mostly for producing land-use maps of project areas and for estimating rates of land-use change or deforestation in the project formulation phase. However, remote-sensing technology has potential for monitoring compliance of forest protection projects and trends in plantation or agroforestry establishment at the subnational to national scales. Monitoring of improved forest management or secondary forests, particularly in the tropics, is difficult with the current suite of satellites, but future development and launching of new satellites may overcome this problem.

Not all remotely-sensed monitoring activities need to use data from satellites. Because forestry projects have well-defined boundaries and are relatively small in area (several thousand to hundreds of thousand hectares), remotely-sensed data from

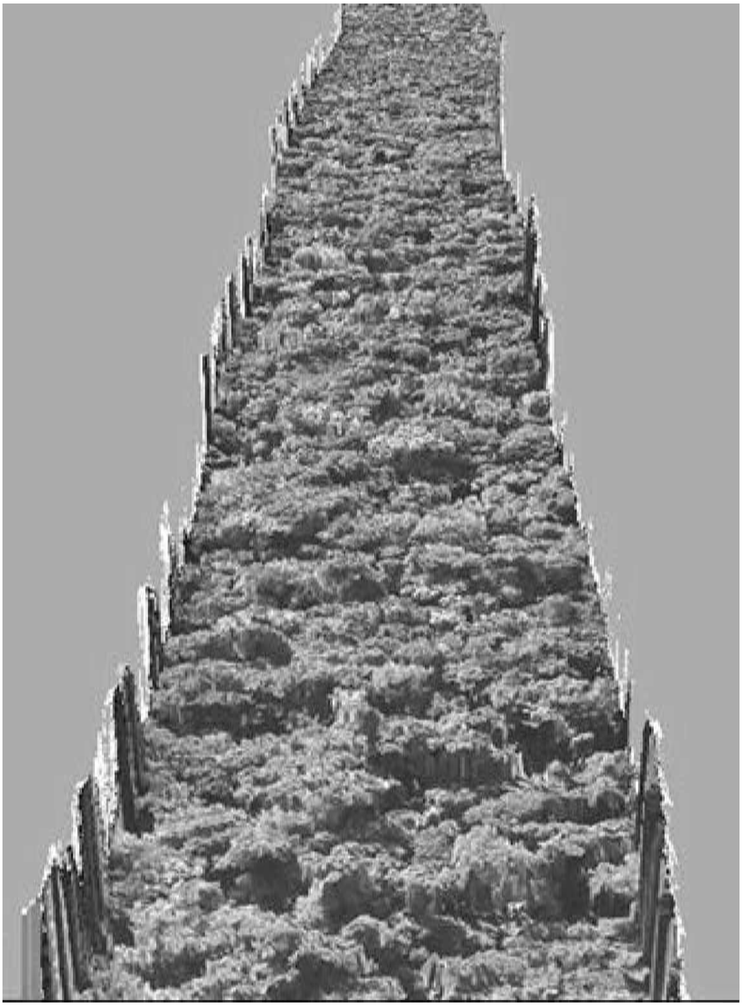

Figure 1. 3D digital image (colour image converted to black and white) of a forest transect in the Noel Kempff Climate Action Project captured by the dual-camera videography system (Reproduced with permission from Dana Slaymaker (Winrock International).)

low-flying airplanes can be used for monitoring. A promising advance in this area couples dual-camera digital videos (wide-angle and zoom) with a pulse laser profiler, data recorders, and differential GPSs (geographical-positioning systems) mounted on a single engine plane (D. Slaymaker 2000, personal communication; EPRI 2001). Transects can be flown over project areas at any desired density. Computer interpretation of the digital imagery collected by this system is able to produce three-dimensional (3D) images (figure 1) from which measures of crown diameter and tree height (from the pulse laser) for individual trees are made. Correlations between crown diameter and DBH are then used to estimate tree diameter for all trees within 'plots' and these DBH estimates are then used to estimate biomass and carbon using the standard regression equations described above. For one forest stratum in the Noel Kempff Project in Bolivia (mixed liana forest, see below for more details of this project), ground measurements gave a mean carbon content in the aboveground trees of 89.6 tC ha^{-1} with a 95% confidence interval of 7.8 tC ha^{-1}, and videography measurements gave a mean of 87.7 tC ha^{-1} with a 95% confidence interval of 5.4 tC ha^{-1} or, in other words, the same value as from the ground measurements but with higher precision (EPRI 2001).

5. Pilot project experience

In this section I present the results of two pilot projects that have different designs for measuring and monitoring the carbon benefits. I present the results of the first set of field measurements in the project areas to establish the initial carbon stocks. Further discussion of the without-project baseline for the Noel Kempff Project is given in Brown *et al*. (2000*a*).

(*a*) *The Noel Kempff Climate Action Project, Bolivia*

In 1996, the government of Bolivia, the Bolivian organization Fundación Amigos de la Naturaleza (FAN), American Electric Power and The Nature Conservancy (TNC) designed a forest-based joint implementation pilot project to allow for the expansion of Noel Kempff Mercado National Park. PacifiCorp and British Petroleum America (now BP Amoco) joined the project in 1997. The duration of this $9.5 million project is 30 years. This project, located in northeastern Bolivia in the department of Santa Cruz, is the largest pilot forestry project to date to be implemented in terms of its area (*ca.* 634 000 ha), funds invested and projected carbon offsets. Further details of this project are given in Brown *et al*. (2000*a*).

The project obtains carbon benefits from two main activities:

(i) averted logging where removal of commercial timber and the associated damage to unharvested trees has been halted; and

(ii) averted conversion of forested lands to agricultural uses where loss of carbon in forest biomass and soil has been halted.

(i) *Inventory of carbon pools*

The project design for measuring the carbon pools is based on the methodology and protocols in MacDicken (1997*a*). The carbon inventory of the area was based on data collected from a network of permanent plots, located using a differential GPS (DGPS). A total of 625 plots was established across the project area with the number of plots sampled in a given strata based on the variance of an initial sample of plots in each strata, the area of the strata, and the desired precision level (±10%) with 95% confidence (table 2). A fixed area, nested plot design was used (4 m radius plot for trees with DBH of greater than or equal to 5–20 cm, and 14 m radius for trees with DBH $\geqslant$ 20 cm) and the following components were measured in each plot: all trees with DBH $\geqslant$ 5 cm, understorey, fine litter, standing and lying dead wood†, and soil to 30 cm depth (table 2). Tree biomass was estimated from

† In the original inventory in 1997, lying dead wood was not measured; a subset of 55 plots were measured in 1999 and a ratio of lying dead wood to live dead wood was calculated and used to estimate the quantity of lying dead wood in the unmeasured plots.

Table 2. *Estimates of carbon stocks* (tC ha^{-1}) *and total carbon content in the forests of the Noel Kempff Climate Action Project (from Delaney et al. 2000)*

S (no. of plots)	A	AG	P	SD	LD	U	L	BG	S	M
tall evergreen (171)	226 827	129	0.5	4.1	11.0	2.0	3.6	25.8	26.9	203
liana (131)	95 564	56	0.5	2.3	4.7	3.8	4.0	11.1	39.9	122
tall flooded (64)	99 316	132	1.1	3.2	11.3	1.9	3.1	26.4	44.8	224
short flooded (35)	49 625	112	0.2	3.0	9.6	2.1	2.9	22.3	55.5	207
mixed liana (218)	159 471	90	1.5	4.4	7.7	2.6	4.3	17.9	24.4	152
burned (6)	3 483	57	0.2	1.6	4.9	0.9	4.2	11.4	36.0	116
total area	643 286									
weighted mean		106.7	0.8	3.6	9.1	2.4	3.7	21.3	33.3	181
total carbon content (Mt)		114.9								
95% CI, % of mean		4.2								

S, strata; A, area in ha; AG, aboveground woody; P, palm; SD, standing dead; LD, lying dead; U, understorey; L, litter; BG, below ground; S, soil; M, mean; CI, confidence interval.

a general biomass regression equation for moist tropical trees (Brown 1997); the validity of this equation was confirmed with the destructive harvest of two large-diameter trees. Biomass regression equations for early colonizing tree species and palms were developed by destructive harvesting of a sample of individuals of such species. Root biomass was estimated from root-to-shoot ratios given in Cairns *et al.* (1997).

The total amount of carbon in the project area was *ca.* 115 MtC, most of which was in aboveground biomass of trees (60%), followed by soil to 30 cm depth (18%), roots (12%) and dead wood (7%); the understorey and fine litter accounted for *ca.* 3% of the total. The 95% confidence interval of the total carbon stock was ±4%, based on sampling error only; regression and measurement error were not included. Inclusion of the error due to regression and measurement is likely to increase the total error to no more than double, as the sampling error has been shown to be the largest source of total error (up to 80% or more) in measuring carbon stocks (Phillips *et al.* 2000).

From this pilot project, encompassing several strata of complex tropical forests, the measurement of carbon stocks can be accomplished with a high degree of precision: the key is to establish the required number of plots to reach the targeted precision levels ahead of time and to install the required number of plots.

(ii) *Future monitoring*

For the averted deforestation component, very little additional carbon monitoring is planned, because it is expected that the change in the carbon content of the existing forest will grow little over this time. The key component of this activity is to ensure that the forest is not being cleared: it is planned to monitor this remotely with this digital dual-camera videography technology described above.

For the averted logging component, the monitoring plans call for five-year interval remeasurement of a set of paired plots (about 100 paired plots) in a nearby proxy concession that was established to measure the amount of dead biomass produced during the felling of a tree and associated activities such as yarding and skidding, as well as the rate of regrowth after harvesting and without harvesting. The remeasurements will be used to determine any delayed mortality and determine any differences in carbon accumulation rates between logged and unlogged plots. These data will be used to revise the carbon benefits as necessary. After two remeasurement times, the plans call for the establishment of an additional set of paired plots in another harvested block to determine whether logging practices are changing over time. Research is underway to adapt the videography system to monitor this impact.

(*b*) *The Guaraqueçaba Climate Action Project, Brazil*

The Guaraqueçaba Climate Action Project (GCAP), located in the Atlantic forest in Paraná, Brazil, is being developed by Central and South West Services (now AEP), TNC and SPVS. The project area is located within the Guaraqueçaba Environment Protection Area (APA), a Federal Reserve of 775 000 ha. The existing project area of *ca.* 4500 ha has *ca.* 15% of the lands in pasture, 20% of the land in young to very young secondary forests and 65% of the land in late secondary forests; all these forests have been disturbed or cleared in the past. The project involves the purchase of water-buffalo ranches with plans to protect all remaining forests, reforest some of the pasture lands with native species, allow the remaining pasture to regenerate naturally, and allow regrowth in the secondary forests over a 40-year life.

The carbon benefits of this project result from emissions avoidance (protection from deforestation) and carbon sequestration (reforestation and natural regeneration of areas with pasture, enrichment planting and recovery of successional forests areas). In the absence of the project, it is expected that the lowland forests would continue to be cleared and degraded and upland forests would continue to be degraded. With the project, lands that were threatened with deforestation are being protected and degraded lands reforested.

(i) *Inventory of carbon pools*

The approach taken for this project is generally the same as that described above for the Noel Kempff Project. Using a combination of remote-sensing data and on-the-ground measurements, the project area has been classified into four forest (based on disturbance and successional stage) and three non-forest (based on presence/absence of shrubs) strata upon which the carbon benefits from this project will be estimated. The total number of plots established in the initial inventory was 168, a number based on initial field measurements in each strata as described above for the Noel Kempff Project. Using criteria described above, the main carbon pools included in this project were live trees to a minimum diameter of 2.5 cm, dead wood, roots, and soil (to 30 cm depth), litter and understorey in the younger forest strata.

For the initial inventory, the total carbon pool (excluding soil) in the forest strata is estimated to be *ca.* 446 000 tC with a precision level of 6% of the mean at 95% confidence (table 3). The overall weighted mean carbon content of forests is 112 tC ha^{-1} (table 3), 78% of which is in the live aboveground woody biomass, 13% of which is in roots, 7% of which is in dead wood, and *ca.* 2% of which is in litter and understorey combined (S. Brown & M. Delaney 2000, unpublished report). Litter and understorey were not measured in the altered mature forest, as it was assumed to be an insignificant component and not worth the time and cost to measure (even in the

Table 3. *Estimates of the carbon stocks* ($tC\ ha^{-1}$) *and total carbon content for the forest strata of the Guaraqueçaba Climate Action Project, Brazil*

(Content includes trees, roots, understorey, dead wood and litter, but excludes soils. Mean ($tC\ ha^{-1} \pm 95\%$ CI) 111.9 ± 6.8; total (tC) 445 464; 95% CI (% of mean) 6.1. Results from S. Brown & M. Delaney (2000, unpublished report). CV, coefficient of variation.)

strata	mature altered $n = 69$	medium/ advanced $n = 46$	young $n = 13$	very young $n = 12$
area (ha)	763.0	2269.6	583.9	363.8
mean	153.5	113.5	96.5	40.3
min	73.6	65.1	41.1	5.7
max	398.7	197.4	203.7	73.2
variance	2638.6	952.4	2280.7	414.7
standard error	6.2	4.6	13.2	5.9
CV (%)	34	27	50	51

advanced/medium stratum, litter and understorey represented less than 2% of the total vegetation pool).

Soil carbon (in the top 30 cm) was measured in the two young forest strata only because these are the only strata likely to produce measurable changes in soil-carbon content over the project life, and a baseline value needed to be established. The total carbon in the soil of these two strata is 59 377 t with a 95% confidence interval of 13% of the mean. Establishment of additional plots in these two young strata is planned for 2002, to decrease the variation in the vegetation and soil-carbon pools.

(ii) *Future monitoring*

The carbon content of the pasture/shrub formations has been estimated to develop the baseline carbon content. As these formations are restored with native tree species and undergo succession, permanent plots will be established in them and remeasured at five-year intervals over the length of the project. The number of plots to be established will be based on the variance of the lowland advanced to medium successional forests as this will be the target forest and its variance will likely reflect the variance of the restored forest.

As significant carbon benefits are expected from the protection of the forests from further degradation, the plots established during the initial inventory will be remeasured at 5-year intervals during the length of the project. As these are permanent plots with tagged trees and mapped dead wood, the changes in carbon stocks will be able to be measured directly; this will result in smaller errors.

6. Other measuring and monitoring issues

(*a*) *Future monitoring tools*

Although the above projects call for ongoing monitoring of carbon stocks, and at present it is planned that this will be done by revisiting the permanent plots, new technological advances are likely to produce systems that can monitor carbon stocks remotely, after some initial calibration. The dual-camera videography system described above is one such advance that is showing high promise for accomplishing this task (EPRI 2001).

(*b*) *Data quality and archiving*

To develop a reliable baseline and a measurement and monitoring plan for both the initial and future measurements of carbon-offset projects, steps must be taken to control errors in sampling and analysis. To accomplish this and to ensure the quality and credibility of the estimates of the quantities of carbon sequestered and/or retained, a quality assurance and quality control (QA/QC) plan is necessary as part of any project's protocol. This plan should include formal procedures to verify methods used to collect field data and the techniques to enter and analyse data. A set of standard operating procedures (SOPs) for all aspects of the field and laboratory activities should be part of the project's documents. To ensure continuity it is also important that all data collected use the same procedures during the project life and are archived using acceptable standards by all partners involved in the project. Adhering to these procedures will ensure that in the event that there is a change in personnel among participating organizations, or if any of the people involved are questioned about any aspect of the project, all will be well informed.

Carbon-offset projects of the type described here are still in their infancy, and must hold up to the scrutiny of the scientific community as well as outside organizations who will ultimately verify the carbon-offsets resulting from project activities. The QA/QC plan must be part of the project's set of documents to be available for review and inspection. The QA/QC plan and SOPs should be updated as necessary when new field equipment or procedures become available.

Because of the relatively long-term nature of these projects, data archiving (maintenance and storage) will be an important component of the work. Original field sheets, laboratory analysis, data analyses, reports, models, assumptions, etc., should all be kept in their original form as well as in some form of electronic media and all of these should be kept in a dedicated and safe place, preferably in more than one place. When storing data in an electronic form one has to keep in mind the rapid pace at which software and hardware are changing; all data should be stored in a form that is likely to be retrievable as new software is developed. What form the data needs to be stored in needs to be investigated further.

7. Verification

Verification of projects is akin to auditing in the financial world and offers a way to provide credibility and transparency of a project's claims to concerned entities such as regulatory bodies, investors, etc. Internal verification could be accomplished by implementation of the QA/QC plan as described above. External or third-party verification could be based on an assessment of the project's compliance with a set of defined eligibility criteria. A single set of internationally accepted eligibility criteria would facilitate direct comparisons of projects, while a variety of such criteria may result in projects and their carbon benefits of differing quality (Moura Costa *et al.* 2000).

Verification activities may include:

(i) evaluation of the project in relation to eligibility criteria based on requirements of international protocols (e.g the Kyoto Protocol);

(ii) review of project's documentation for estimating the carbon benefits (e.g. procedures, methodologies, analyses, reports);

(iii) inspection or calibration of measurement and analytical tools and methods;

(iv) repeat sampling and measurements of carbon stocks;

(v) assessment of the quality and comprehensiveness of the data used in calculating the project baseline and offsets and therefore the confidence in the final claims;

(vi) assessment of risks associated with the project and the carbon benefits; and

(vii) the presence or absence of non-greenhouse gas externalities such as environmental and social impacts (Trines 1998; Moura Costa *et al*. 2000; Brown *et al*. 2000*b*).

To date there has been little experience with third-party verification of carbon benefit claims of projects (Moura Costa *et al*. 2000). The lack of policy guidelines related to verifying the design and implementation of projects results in a range of methods and approaches being used, leading to discrepancies between claims of different projects. This in turn leads to uncertainty, and thus raises concerns about the use of forestry projects for abating carbon emissions. To improve this situation and lead to the implementation of consistently credible projects, international agreement is needed in relation to protocols used for: determining additionality, baselines and leakage; estimating uncertainty and measurement error; accounting and calculating carbon benefits; determining precision levels required for quantification of carbon benefits; and determining time-frames over which projects are implemented (Moura Costa *et al*. 2000). Finally, international policy makers must establish an accreditation body to certify and oversee project verification.

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