CARBON ASSESSMENT MANUAL

WESTERN KENYA INTEGRATED ECOSYSTEM MANAGEMENT PROJECT

World Agroforestry Centre
TRANSFORMING LIVES AND LANDSCAPES

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Summary

This document combines the Monitoring Plan, Carbon Sequestration Predictions and the Verification Protocols of the planned Western Kenya Integrated Ecosystem Management Project (IEM). The IEM Project is intended to assist rural communities in the Nyando and Yala River catchments to understand and practice land managements, largely through agroforestry interventions, that provide a wide range of environmental services including biodiversity and watershed protection, land restoration and climate change mitigation. While doing so, recognizable short-term benefits will serve as economic incentive to practice land managements that are associated with these longer-term environmental services. This Monitoring Plan is a tool that guides information gathering and verification activities essential to the evaluation of the IEM project. The Monitoring Plan is built upon an accompanying Baseline Study, complies with the principles of the Clean Development Mechanism and is intended to serve as the technical component for the environmental services achieved within the community-based activities described within the main Western Kenya IEM Project Document.

Carbon Measurement. One of the challenges in developing a carbon offsets project involving communities of smallhold farmers is to document carbon gains at considerably less expense than the value of the carbon, otherwise the groups of land managers do not benefit fully from their collective actions. This monitoring plan includes a tree-based approach to establishing system carbon gains that relies upon tabular values to estimate C gains, and spreadsheet software to aggregate these gains between locations and over time (pp. 4-14). This system may accommodate community agroforestry initiatives to periodically document the number, survival and growth of their trees. Detailed procedures for verifying the carbon estimates are also provided in this section (pp. 15-20).

Carbon Projections. A scenario of carbon offsets within the project assumes that 400 trees per hectare are planted at the onset of rains in April 2004 on 2500 ha. After 10 years, carbon gains are about 477,000 t CO_2 ER valued between \$1.4 and \$1.9 million, at \$3 and \$4 t, respectively. Of this C, 69% resides in aboveground tree biomass and 25% in roots. At the end of 2012, the end of first round of CDM commitment, emission reductions are approximately 356,000 t CO_2 (Figure 5). Admittedly, this projection is somewhat simplistic in that it assumes all 1 million trees (400 trees ha^{-1} x 2500 ha) are planted in a single year, tree growth rates remain uninterrupted by periodic drought, and that all trees survive throughout the lifetime of the project. Nonetheless, the projection demonstrates that the Integrated Environmental Management Project in western Kenya will operate at sufficient scope to produce carbon offsets for trading. A projection that included a 50% reduction in DBH increase one in every three years as could be expected from frequent drought resulted in the 32% reduction of CO_2 ER by 2020, suggesting that the project remains viable despite unfavorable mid-term weather conditions. The Carbon Sequestration Projections section (pp. 21-27) includes a list of assumptions and conversion factors, and describes the spreadsheet upon which the projections are based and that may be, when necessary, amended.

Biodiversity Assessment. Two complimentary approaches to monitoring agro-biodiversity are considered in this section. The first approach, A Rapid Approach to Biodiversity Assessment, consists of a pair-wise plant checklist of 84 useful, common exotic and indigenous plants (pp. 28-38). This checklist is intended for use by surveyors lacking detailed taxonomic knowledge and operates at a "whole-farm" level. The presence of plants may also be weighed in terms of their abundance, and frequently encountered plants not appearing on the checklist may be "written in" for consideration. The density and relative frequencies of plant species may be calculated from the checklist, and indicators of the importance of traditional, indigenous plants

calculated. Also included within this section is a second checklist of 84 indigenous species occurring within the Lake Victoria Regional Mosaic and adjacent afro-montane ecosystems (pp. 36-38). Stronger plant taxonomic skills are required to use this checklist, and it is not likely that it will be used for purposes other than research within the project. The list does, however, assist surveyors to fill in the open-ended sections of the Rapid Approach as necessary as well as supporting the detailed floristic studies planned at the beginning and end of the project

Verification Protocols. A section on Verification Protocols (pp. 39-44) is included within this Monitoring Plan. This section identifies candidate key indicators of project success, and suggests the assignment of operational responsibilities within the project based upon the establishment and interactions of five project teams. One of the teams is led by a Community Liaison Specialist whose assignment is to recruit and monitor the participation of grassroots associations within the project. Several of the key indicators identified within this section (pp. 39-40) may also be considered as "triggers" of carbon and biodiversity gains, water quality improvement, household wellbeing and other project goals. This section corresponds to the Monitoring Plan "Task 3", the development of a Management and Operational Systems Monitoring Plan although carbon verification protocols are covered, in this document, within the Carbon Sequestration Projections section under Aggregate Carbon Gains and Sensitivity Analysis (pp. 26-27) and in the MS Excel files *Aggregate C Gains.xls* and *C Projection Utility.xls*. The aggregate C calculation spreadsheet allows for the inclusion or separation of above- and below-ground C gains, and the adjustment of and separation of both root and soil C sequestration as user options.

Recordkeeping and Communications Procedures. Also included within this Verification Protocols section are guidelines for Recordkeeping and Communications Procedures (pp. 43-44). Many of the records to be maintained are based upon the standardized data forms for C gains and biodiversity assessment, while others are based upon approaches developed through the baseline study. Greater flexibility is provided to the project staff addressing the social benefits accrued through the IEM Project owing to the need for site-specific and informal observations within socio-economics as an area of study. This sub-section suggests that several databases be developed by different project participants, including a project internet website, registry of participating community groups and land managers and a spatially-referenced environmental data set that may be used to produce images used to document project gains with a Geographic Information System. Suggestions for many other records to be maintained and shared are included under the areas of Project Information, Carbon Gains, Biodiversity Status, Land and Water Quality, Social Benefits and On-farm Activities. This sub-section not only stresses recordkeeping, but also the manner in which project developments will be communicated among project partners and to client land managers. Recordkeeping is important within this project, but more so is the development of reliable channels of information flow throughout the project and to the Kenyan public and international audiences.

The Western Kenya Integrated Environmental Management Project is a challenging undertaking in that it combines the efforts of several organizations operates at several scales, from the catchment-level to the individual farm enterprise. The Monitoring Plan and its Verification Protocols are intended to assist in launching the project, and should not be viewed as "written in stone". For example, initiating agroforestry-based carbon offset projects is a challenging undertaking by itself, yet it is only one of several planned project undertakings. Project scientists are encouraged to regard the protocols and data forms included within this Monitoring Plan as platforms for their additional creative inputs, particularly to find ways to link carbon sequestration, biodiversity, land restoration, water quality and household wellbeing as interactive goals. This will prove no easy task and hopefully the approaches described in this Monitoring Plan will assist them in their worthy efforts.

Carbon Sequestration: Background and Definitions

Background. One of the most important planned environmental benefits resulting from project activities will be the establishment of trees through agroforestry in a manner that is compliant with the Clean Development Mechanism, allowing for that carbon to be traded to others requiring carbon offsets. Two particularly important elements of that compliance are that project activities not be established in areas with forests cleared after 1990 and that all C gains be related to afforestation and reforestation (Noble and Scholes, 2001). The project will establish guidelines where C offset enterprises adhere with key principles of legal requirements, farmers' land use rights, fair payment, permanence and ecosystem health as established by The World Agroforestry Centre (Simons, 2003). This section describes the process through which the carbon gains resulting from smallholder agroforestry may be monitored in a cost and time-efficient manner, field protocols for validating C stocks and projected C gains from agroforestry enterprises. The monitoring protocols will be:

1. conducted at least once per year at all locations and based upon the tree diameter at breast height measured by participants and supervised by project scientists
2. standardized across project locations and during repeated measures, and be appropriate for confirming baselines at the onset of the project
3. consider not only aboveground tree biomass C, but also estimates of root biomass C and soil C gains based upon conservative conversion factors
4. calculated as both "hard copy" data forms and through use of an "Excel Workbook" (spreadsheet) with options to either include or exclude below-ground C and to adjust key conversion factors as acceptable to carbon traders
5. sufficiently flexible to allow for the development of improved allometric equations and conversion factors during the course of the project
6. used to calculate the C gains resulting from individual farm enterprises, participating grassroots groups and for the project as a whole during the project lifetime.

Carbon gains from agroforestry enterprises are projected over time based upon expected tree growth rates, but may also result from aggregating measured DBH across farms and project locations. This aggregation serves as the core spreadsheet software that will be used to monitor the project with a mixed tree enterprise scenario and its sensitivity analyses included within the projections.

Some useful definitions

Breast height: a point along the stem of a tree 1.3 m above the soil level at which the diameter of a tree is measured. Tree diameter measured at this point is DBH

Carbon sequestration: the capture and secure storage of carbon that would otherwise be admitted to and remain in the atmosphere, primarily as carbon dioxide (CO_2). **Carbon offsets** refer to quantified sequestration.

Emission reductions (ER): the equivalent of CO_2 contained in carbon sequestered through a deliberate, document management of resources, in the case of this document C gains in woody biomass and soil where ER (t) = C x (3.67). Note: 3.67 is the ratio of the molecular weight of CO_2 (44) and the atomic weight of C (12).

Plot: any area of land of any shape or size used for sampling. In the case of carbon estimation in farming systems, plots may consist of individual enterprises and land uses.

Quadrat: refers to a predetermined rectangular area where plant biomass samples are recovered with the recommended sizes of 30 m x 30 m for woody vegetation and 1 m x 1 m for understorey and herbs (*plural* quadrates).

Transect: A line of known length that defines vegetation selected for sampling and may also consist of a "string" of contiguous quadrates.

Visualizing Carbon: A Shortcut Method Based upon Tabular Values

It is unrealistic to expect individuals or communities to protect and foster that which they do not understand, and this is certainly the case for carbon stocks in smallhold farming systems. Carbon exists as an inseparable component of vegetation, litter and soil organic matter, and is primarily lost as an invisible gas (CO_2), factors which complicate the understanding of carbon stocks and dynamics to non-scientists. When asked what is the likely crop yield of maize in a maturing field or meters of poles in a woodlot, a land manager can often provide an educated guess, but this is not the case for system C stocks within those same land uses. Carbon seems too intangible for approximation. Yet carbon is predictable from certain perspectives. It is a near constant proportion in vegetation (47%).

Tree Carbon. An important empirical relationship exists between the tree diameter at breast height (DBH) of trees and tree aboveground biomass. Allometric equations based upon power functions, which intercept the origin, are recommended above quadratic approaches because of their greater accuracy for assigning biomass to smaller trees. For general purposes, we recommend the equations from FAO (1997) in Dry Zones (<1500 mm yr^{-1}):

$$\textit{Aboveground tree biomass (kg tree}^{-1}\textit{)} = \exp^{(-1.996 + 2.32 \ln D)}$$

and in Moist Zones (1500-4000 mm yr^{-1}):

$$\textit{Aboveground tree biomass (kg tree}^{-1}\textit{)} = \exp^{(-2.134 + 2.53 \ln D)}$$

where Y is the aboveground tree biomass in kg, exp = 2.71828… and D is the measured DBH in cm. Other equations are available for drier (<900 mm yr^{-1}) and wet zone (>4000 mm yr^{-1}) from FAO (1997). Allometric equations may be further refined by including factors for tree height and wood density (Ketterings, 2001). Measurement of tree diameter is easily made using either a diameter tape or callipers (page 15) but the mathematics required to convert from diameter to biomass is probably too complex for most land managers in Africa. Tree diameter (D) is readily calculated from tree circumference (C) by division by pi (π = 3.14159…) where C = D x π.

A simple table was prepared that allows for the estimation of carbon resulting from planting trees based upon established biophysical relationships. Table 1a provides the total C (in tons) contained in above- and below-ground woody biomass of different sized trees based upon a widely employed allometric relationship (FAO, 1997) between tree diameter at breast height (DBH) and total tree biomass. Table 1b contains estimates of total carbon gains resulting from the same trees based upon conservative assumptions of C in roots (+0.35) and the turnover of leaf drop (0.15 woody biomass) and fine roots (0.15 woody biomass) assuming modest (0.12) annual C sequestration in soil. Tables 1a and 1b both provide estimates of total C resulting from different sizes and numbers of growing trees. To use these tables, one matches the number and sizes of trees of interest. For example, in Table 1a, a row of 10 trees that have grown to 30 cm diameter contain 2.30 t of carbon. The aboveground biomass C is presented in Appendix 1, and should be used when neither roots nor soil C gains are being considered.

The tree biomass carbon relationship is independent of land area, so that tree numbers (rows) may be obtained from different size categories (columns) and the carbon stocks estimated for any known land area, such as different sized smallholdings. One shortcoming is that carbon stocks may not be readily interpolated between columns because of the exponential nature of the allometric function. In other words, tree biomass C for a tree 27.5 cm in diameter does not occur midway between the 25 and 30 cm diameters but is skewed toward the higher diameter.

Table 1. Estimates of tree C in above- and below-ground biomass (Table 1a) resulting from tree biomass of different diameters based on aboveground biomass (AGB) and in tree biomass C combined with anticipated soil carbon gains (Table 1b) assuming that AGB C = 0.47 x $\exp^{(-1.997 + 2.32 (\ln DBH))}$, root biomass = 0.35 AGB, leaf drop = 0.15 AGB, fine root turnover = 0.15 AGB, soil sequestration = 0.08 t SOC t^{-1}, leaf and fine root inputs and annual SOC turnover = 0.625.

a. tree biomass C only

tree	DBH (cm)																
number	5	7.5	10	12.5	15	20	25	30	35	40	45	50	60	70	80	90	100
	increased tree and soil C (tons)																
1	0.00	0.01	0.02	0.03	0.05	0.09	0.15	0.23	0.33	0.45	0.59	0.75	1.15	1.65	2.24	2.95	3.76
2	0.01	0.02	0.04	0.06	0.09	0.18	0.30	0.46	0.66	0.90	1.18	1.51	2.30	3.29	4.49	5.89	7.53
3	0.01	0.03	0.05	0.09	0.14	0.27	0.45	0.69	0.99	1.35	1.77	2.26	3.45	4.94	6.73	8.84	11.29
4	0.01	0.04	0.07	0.12	0.18	0.36	0.60	0.92	1.32	1.80	2.36	3.01	4.60	6.58	8.97	11.79	15.05
5	0.02	0.05	0.09	0.15	0.23	0.45	0.75	1.15	1.65	2.25	2.95	3.77	5.75	8.23	11.21	14.74	18.82
6	0.02	0.06	0.11	0.18	0.28	0.54	0.91	1.38	1.98	2.69	3.54	4.52	6.90	9.87	13.46	17.68	22.58
7	0.03	0.06	0.13	0.21	0.32	0.63	1.06	1.61	2.31	3.14	4.13	5.28	8.05	11.52	15.70	20.63	26.34
8	0.03	0.07	0.14	0.24	0.37	0.72	1.21	1.84	2.64	3.59	4.72	6.03	9.20	13.16	17.94	23.58	30.11
9	0.03	0.08	0.16	0.27	0.42	0.81	1.36	2.07	2.97	4.04	5.31	6.78	10.35	14.81	20.18	26.53	33.87
10	0.04	0.09	0.18	0.30	0.46	0.90	1.51	2.30	3.29	4.49	5.90	7.54	11.51	16.45	22.43	29.47	37.63
15	0.05	0.14	0.27	0.45	0.69	1.35	2.26	3.46	4.94	6.74	8.85	11.31	17.26	24.68	33.64	44.21	56.45
20	0.07	0.18	0.36	0.60	0.92	1.80	3.02	4.61	6.59	8.98	11.80	15.07	23.01	32.90	44.85	58.95	75.27
25	0.09	0.23	0.45	0.76	1.15	2.25	3.77	5.76	8.24	11.23	14.76	18.84	28.76	41.13	56.06	73.68	94.08
30	0.11	0.28	0.54	0.91	1.38	2.70	4.53	6.91	9.88	13.47	17.71	22.61	34.52	49.35	67.28	88.42	112.90
40	0.14	0.37	0.72	1.21	1.85	3.60	6.04	9.22	13.18	17.96	23.61	30.15	46.02	65.81	89.70	117.89	150.54
50	0.18	0.46	0.90	1.51	2.31	4.50	7.55	11.52	16.47	22.46	29.51	37.68	57.53	82.26	112.13	147.36	188.17
60	0.22	0.55	1.08	1.81	2.77	5.40	9.06	13.82	19.77	26.95	35.41	45.22	69.03	98.71	134.56	176.84	225.80
70	0.25	0.65	1.26	2.12	3.23	6.30	10.57	16.13	23.06	31.44	41.32	52.76	80.54	115.16	156.98	206.31	263.44
80	0.29	0.74	1.44	2.42	3.69	7.20	12.08	18.43	26.36	35.93	47.22	60.29	92.04	131.61	179.41	235.78	301.07
90	0.32	0.83	1.62	2.72	4.15	8.09	13.58	20.74	29.65	40.42	53.12	67.83	103.55	148.06	201.83	265.26	338.71
100	0.36	0.92	1.80	3.02	4.61	8.99	15.09	23.04	32.95	44.91	59.02	75.37	115.05	164.52	224.26	294.73	376.34

b. tree biomass and soil C gains

tree	DBH (cm)																
number	5	7.5	10	12.5	15	20	25	30	35	40	45	50	60	70	80	90	100
	increased tree and soil C (tons)																
1	0.00	0.01	0.02	0.03	0.05	0.09	0.16	0.24	0.35	0.47	0.63	0.81	1.25	1.82	2.54	3.44	4.55
2	0.01	0.02	0.04	0.06	0.10	0.19	0.31	0.48	0.69	0.95	1.25	1.61	2.50	3.64	5.08	6.88	9.09
3	0.01	0.03	0.06	0.09	0.14	0.28	0.47	0.72	1.04	1.42	1.88	2.42	3.75	5.46	7.63	10.31	13.64
4	0.01	0.04	0.07	0.12	0.19	0.37	0.63	0.96	1.38	1.90	2.51	3.22	5.00	7.28	10.17	13.75	18.18
5	0.02	0.05	0.09	0.16	0.24	0.47	0.78	1.20	1.73	2.37	3.13	4.03	6.25	9.11	12.71	17.19	22.73
6	0.02	0.06	0.11	0.19	0.29	0.56	0.94	1.44	2.07	2.84	3.76	4.83	7.49	10.93	15.25	20.63	27.28
7	0.03	0.07	0.13	0.22	0.33	0.65	1.10	1.68	2.42	3.32	4.39	5.64	8.74	12.75	17.79	24.07	31.82
8	0.03	0.08	0.15	0.25	0.38	0.74	1.26	1.92	2.77	3.79	5.01	6.44	9.99	14.57	20.33	27.51	36.37
9	0.03	0.09	0.17	0.28	0.43	0.84	1.41	2.16	3.11	4.26	5.64	7.25	11.24	16.39	22.88	30.94	40.91
10	0.04	0.09	0.19	0.31	0.48	0.93	1.57	2.41	3.46	4.74	6.26	8.05	12.49	18.21	25.42	34.38	45.46
15	0.06	0.14	0.28	0.47	0.71	1.40	2.35	3.61	5.19	7.11	9.40	12.08	18.74	27.32	38.13	51.57	68.19
20	0.07	0.19	0.37	0.62	0.95	1.86	3.14	4.81	6.91	9.48	12.53	16.11	24.98	36.42	50.84	68.76	90.92
25	0.09	0.24	0.46	0.78	1.19	2.33	3.92	6.01	8.64	11.84	15.66	20.13	31.23	45.53	63.55	85.96	113.65
30	0.11	0.28	0.56	0.93	1.43	2.79	4.71	7.22	10.37	14.21	18.79	24.16	37.47	54.63	76.26	103.15	136.38
40	0.15	0.38	0.74	1.25	1.90	3.72	6.28	9.62	13.83	18.95	25.06	32.22	49.96	72.84	101.67	137.53	181.84
50	0.18	0.47	0.93	1.56	2.38	4.66	7.84	12.03	17.28	23.69	31.32	40.27	62.45	91.05	127.09	171.91	227.30
60	0.22	0.57	1.11	1.87	2.86	5.59	9.41	14.43	20.74	28.43	37.59	48.32	74.94	109.26	152.51	206.29	272.76
70	0.26	0.66	1.30	2.18	3.33	6.52	10.98	16.84	24.20	33.17	43.85	56.38	87.43	127.47	177.93	240.68	318.22
80	0.30	0.76	1.48	2.49	3.81	7.45	12.55	19.24	27.65	37.90	50.12	64.43	99.92	145.68	203.35	275.06	363.68
90	0.33	0.85	1.67	2.80	4.28	8.38	14.12	21.65	31.11	42.64	56.38	72.49	112.41	163.89	228.77	309.44	409.14
100	0.37	0.95	1.85	3.11	4.76	9.31	15.69	24.06	34.57	47.38	62.65	80.54	124.90	182.10	254.18	343.82	454.59

Extrapolation may be made, however, by extending the values obtained within the rows. In other words the value for 35 trees from a diameter size category is equal to that of 30 trees + 5 trees of that same size category. A table of above-ground tree C based upon DBH useful for the most conservative estimates of tree biomass C appears in Appendix 1.

Crop Carbon. Carbon stocks may also be estimated for crops based upon their yield, harvest index and root-to-shoot ratio. Harvest index is the proportion of aboveground biomass that is removed as crop yield. For example, if a 1 ton crop of maize has a harvest index of 0.35, then the total crop aboveground biomass is 1.00/0.35 or 2.86 t, and the stover is 1.86 t (or 2.86 aboveground – 1.00 t grain). Furthermore, if one assumes that grain, shoots and roots all contain 47% C and that root biomass is 0.35 of shoot biomass, then the total crop carbon at peak biomass before harvest is 1.81 t C (2.86 x 1.35 x 0.47). This relationship may be summarized as:

Peak biomass C = crop C content x (crop yield / harvest index) x (1 + root:shoot ratio)

and when the values above are substituted in the equation:

Peak biomass C = 0.47 x (1.0 / 0.35) x 1.35 = 1.81 t C

This approach was used to develop a table of crop carbon contents for different yields and harvest indices (Table 2). For example, a 2750 kg crop (= 2.75 t) with a harvest index of 0.25 contains 7.0 t C in its grain, shoots and roots, regardless of the land area upon which it was produced. This value refers to the peak biomass carbon, and it should be time-averaged throughout the year based upon the length of the growing season.

Table 2. Total crop carbon (tons of grain, shoots and roots) at peak biomass before harvest (left) and aboveground crop residue C (tons) after harvest for different harvest indices and crop yields assuming 47% C content in biomass and roots are 35% aboveground biomass.

crop	harvest index (%)							harvest index (%)						
yield	10%	15%	20%	25%	30%	35%	40%	10%	15%	20%	25%	30%	35%	40%
(kg)	total crop C (tons) before harvest							crop residue C (tons) after harvest						
500	3.2	2.1	1.6	1.3	1.1	0.9	0.8	2.1	1.3	0.9	0.7	0.5	0.4	0.4
750	4.8	3.2	2.4	1.9	1.6	1.4	1.2	3.2	2.0	1.4	1.1	0.8	0.7	0.5
1000	6.3	4.2	3.2	2.5	2.1	1.8	1.6	4.2	2.7	1.9	1.4	1.1	0.9	0.7
1250	7.9	5.3	4.0	3.2	2.6	2.3	2.0	5.3	3.3	2.4	1.8	1.4	1.1	0.9
1500	9.5	6.3	4.8	3.8	3.2	2.7	2.4	6.3	4.0	2.8	2.1	1.6	1.3	1.1
1750	11.1	7.4	5.6	4.4	3.7	3.2	2.8	7.4	4.7	3.3	2.5	1.9	1.5	1.2
2000	12.7	8.5	6.3	5.1	4.2	3.6	3.2	8.5	5.3	3.8	2.8	2.2	1.7	1.4
2250	14.3	9.5	7.1	5.7	4.8	4.1	3.6	9.5	6.0	4.2	3.2	2.5	2.0	1.6
2500	15.9	10.6	7.9	6.3	5.3	4.5	4.0	10.6	6.7	4.7	3.5	2.7	2.2	1.8
2750	17.4	11.6	8.7	7.0	5.8	5.0	4.4	11.6	7.3	5.2	3.9	3.0	2.4	1.9
3000	19.0	12.7	9.5	7.6	6.3	5.4	4.8	12.7	8.0	5.6	4.2	3.3	2.6	2.1
3250	20.6	13.7	10.3	8.2	6.9	5.9	5.2	13.7	8.7	6.1	4.6	3.6	2.8	2.3
3500	22.2	14.8	11.1	8.9	7.4	6.3	5.6	14.8	9.3	6.6	4.9	3.8	3.1	2.5
3750	23.8	15.9	11.9	9.5	7.9	6.8	5.9	15.9	10.0	7.1	5.3	4.1	3.3	2.6
4000	25.4	16.9	12.7	10.2	8.5	7.3	6.3	16.9	10.7	7.5	5.6	4.4	3.5	2.8
4250	27.0	18.0	13.5	10.8	9.0	7.7	6.7	18.0	11.3	8.0	6.0	4.7	3.7	3.0
4500	28.6	19.0	14.3	11.4	9.5	8.2	7.1	19.0	12.0	8.5	6.3	4.9	3.9	3.2
4750	30.1	20.1	15.1	12.1	10.0	8.6	7.5	20.1	12.7	8.9	6.7	5.2	4.1	3.3
5000	31.7	21.2	15.9	12.7	10.6	9.1	7.9	21.2	13.3	9.4	7.1	5.5	4.4	3.5
5250	33.3	22.2	16.7	13.3	11.1	9.5	8.3	22.2	14.0	9.9	7.4	5.8	4.6	3.7
5500	34.9	23.3	17.4	14.0	11.6	10.0	8.7	23.3	14.6	10.3	7.8	6.0	4.8	3.9
5750	36.5	24.3	18.2	14.6	12.2	10.4	9.1	24.3	15.3	10.8	8.1	6.3	5.0	4.1
6000	38.1	25.4	19.0	15.2	12.7	10.9	9.5	25.4	16.0	11.3	8.5	6.6	5.2	4.2
6250	39.7	26.4	19.8	15.9	13.2	11.3	9.9	26.4	16.6	11.8	8.8	6.9	5.5	4.4
6500	41.2	27.5	20.6	16.5	13.7	11.8	10.3	27.5	17.3	12.2	9.2	7.1	5.7	4.6
6750	42.8	28.6	21.4	17.1	14.3	12.2	10.7	28.6	18.0	12.7	9.5	7.4	5.9	4.8
7000	44.4	29.6	22.2	17.8	14.8	12.7	11.1	29.6	18.6	13.2	9.9	7.7	6.1	4.9
7250	46.0	30.7	23.0	18.4	15.3	13.1	11.5	30.7	19.3	13.6	10.2	8.0	6.3	5.1
7500	47.6	31.7	23.8	19.0	15.9	13.6	11.9	31.7	20.0	14.1	10.6	8.2	6.5	5.3

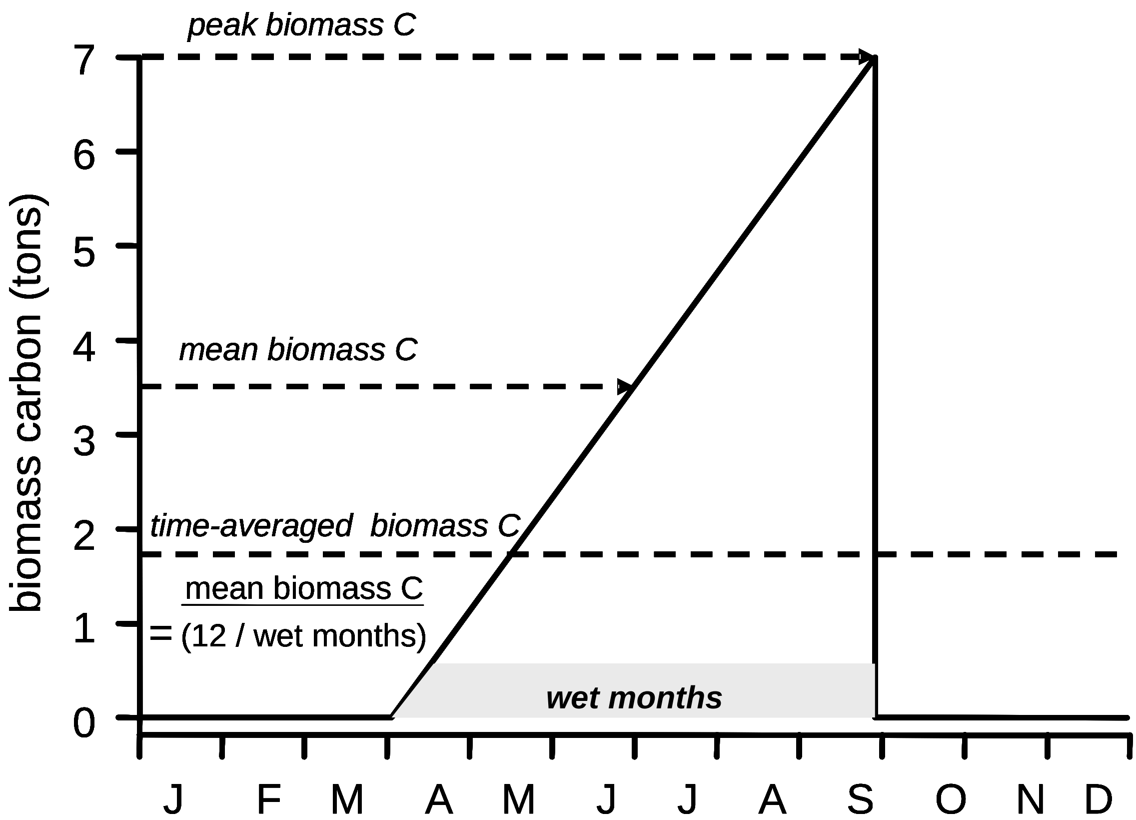

Figure 1. Peak biomass carbon, mean biomass carbon and time-averaged biomass carbon for a crop containing 6.0 t C where mean biomass C = 0.5 x (peak biomass C) and time-averaged biomass C = mean biomass C/(12 / wet months).

Time-averaging requires that the peak season biomass and the number of wet months (the growing season) be known, and is calculated as:

Time-averaged biomass C = (peak biomass C /2) / (12 / wet months)

For example, if the growing season is 6 months during the year, the mean carbon content for the wet season is 3.5 t C (7.0/2). If the fields sit barren during the following dry six months, then the time averaged standing carbon stock is 1.75 t C throughout the year (see Figure 1). As the length of the growing season increases, so does the time-averaged biomass C. These equations also hold for intercrops or bimodal rainfall patters if one combines the two annual crop yields in Table 1 and sums the total wet months. For example, if 3 t maize, with a harvest index of 0.35 is grown in a 5 growing season in the first rains, and 1.5 t beans with a harvest index of 0.25 is produced during the 3 month "short season", then:

Time-averaged biomass C = [(5.4 + 3.8) x 1.35) / 2] / (12 / 8) = 6.13 t C

Land managers may also be interested in the amount of carbon that remains in crop residues following the removal of harvest. This carbon may also be estimated from yield and harvest index data as presented in the right hand portion of Table 2.

Soil Carbon. Large amounts of carbon reside in the soil, but this C may not be as easily estimated as that in trees or crops. The measurement of soil organic carbon requires a laboratory where either wet digestion or dry combustion is performed. The results are expressed as grams of carbon per kilogram of soil (= parts per thousand) or as percent C (= parts per hundred). In general, soils range from about 5 to 25 g kg^{-1}, or 0.5 to 2.5% C. But this value, the carbon content, does not describe how much carbon resides in a particular field unless we know how much the soil weighs Okalebo *et al*., 2002). To convert from volume of soil to the weight of soil, we must also know the soil bulk density, the mass of soil per unit volume, and the depth of soil that is of interest.

$$\textit{Soil C (t ha}^{-1}\textit{) = C content (kg/kg) x bulk density (kg/liter) x (10 x soil depth (l/m}^{2}\textit{)) x 10000 m}^{2}\textit{/ha x (1 t/1000 kg)}$$

and this equation may be further simplified as:

$$\textit{Soil C (t ha}^{-1}\textit{) = C content (kg/kg) x bulk density (kg/l) x soil depth (cm) x 100}$$

In general, soil bulk density ranges between 1.1 to 1.6 kg of soil per liter (= 1000 cubic centimeters) depending on the soil texture. Usually, the plow layer is considered to be 0 to 20 cm depth, and the root zone is from 0 to 50 cm depth. The amount of soil C in one hectare (tons C per ha where 1.0 ha equals 10,000 square meters) to a depth of 20 cm (= 200 l per square meter), with a bulk density of 1.3 and a carbon content of 15 g C per kg soil (= 0.015 kg C per kg soil) is calculated as:

$$\textit{Soil C (t ha}^{-1}\textit{) = 0.015 kg/kg x 1.3 kg/liter x 200 l/m}^{2}\textit{ x 10000 m}^{2}\textit{/ha x 1 t/1000 kg = 39 t C per ha}$$

Again, this equation is rather complex for most non-scientists but tables may be constructed that simplify the task. Table 3 provides the total soil organic carbon per ha in the top 20 cm and 50 cm horizons for soils of different textures (columns) and C contents (rows). In this case it is not possible to generate an estimate independently of land area because the soil C stocks are a direct function of land area and soil depth; therefore, land managers who employ these tables are then expected to adjust their estimate based upon the land area under consideration.

An important feature of Table 3 is its potential for interpolation, as all relationships are linear. For example, the C stock value of a loamy clay or a sandy clay is midway between the tabular values presented within the respective columns. Furthermore, the relationships within this table also may be applied to soil C fluxes as well as stocks. For example, if 10 g C per kg soil is lost due to soil erosion or intensive tillage, that carbon loss (or gain) may be estimated directly from Table 4.

Soil carbon sequestration may be estimated from the amount of organic carbon inputs to soil and their sequestration efficiency. The efficiency of sequestration is related to the soil environment and the chemical characteristics of the organic inputs. In general, cool dry climates result in slower "turnover times" than in hot humid climates, resulting in a proportionately larger contribution to soil C. This relationship of soil C gain immediately following organic input addition may be represented as:

$$\textit{Soil C sequestration = Soil inputs (t ha}^{-1}\textit{) x carbon content (t t}^{-1}\textit{) x Sequestration efficiency t t}^{-1}\textit{)}$$

Table 3. Soil organic carbon (t ha^{-1}) in different textured soils resulting from changes in the soil organic carbon content (g kg^{-1} soil) at two different soil depths (0-20 and 0-50 cm).

soil C gain	loam	clayey loam	clay	loamy sand	sand	loam	clayey loam	clay	loamy sand	sand
	bulk density (kg l-1)									
g C kg soil-1	1.1	1.2	1.3	1.4	1.5	1.1	1.2	1.3	1.4	1.5
	soil C in 0-20 cm (t ha-1)					soil C in 0-50 cm (t ha-1)				
1	2.2	2.4	2.6	2.8	3.0	5.5	6.0	6.5	7.0	7.5
2	4.4	4.8	5.2	5.6	6.0	11.0	12.0	13.0	14.0	15.0
3	6.6	7.2	7.8	8.4	9.0	16.5	18.0	19.5	21.0	22.5
4	8.8	9.6	10.4	11.2	12.0	22.0	24.0	26.0	28.0	30.0
5	11.0	12.0	13.0	14.0	15.0	27.5	30.0	32.5	35.0	37.5
6	13.2	14.4	15.6	16.8	18.0	33.0	36.0	39.0	42.0	45.0
7	15.4	16.8	18.2	19.6	21.0	38.5	42.0	45.5	49.0	52.5
8	17.6	19.2	20.8	22.4	24.0	44.0	48.0	52.0	56.0	60.0
9	19.8	21.6	23.4	25.2	27.0	49.5	54.0	58.5	63.0	67.5
10	22.0	24.0	26.0	28.0	30.0	55.0	60.0	65.0	70.0	75.0
11	24.2	26.4	28.6	30.8	33.0	60.5	66.0	71.5	77.0	82.5
12	26.4	28.8	31.2	33.6	36.0	66.0	72.0	78.0	84.0	90.0
13	28.6	31.2	33.8	36.4	39.0	71.5	78.0	84.5	91.0	97.5
14	30.8	33.6	36.4	39.2	42.0	77.0	84.0	91.0	98.0	105.0
15	33.0	36.0	39.0	42.0	45.0	82.5	90.0	97.5	105.0	112.5
16	35.2	38.4	41.6	44.8	48.0	88.0	96.0	104.0	112.0	120.0
17	37.4	40.8	44.2	47.6	51.0	93.5	102.0	110.5	119.0	127.5
18	39.6	43.2	46.8	50.4	54.0	99.0	108.0	117.0	126.0	135.0
19	41.8	45.6	49.4	53.2	57.0	104.5	114.0	123.5	133.0	142.5
20	44.0	48.0	52.0	56.0	60.0	110.0	120.0	130.0	140.0	150.0
21	46.2	50.4	54.6	58.8	63.0	115.5	126.0	136.5	147.0	157.5
22	48.4	52.8	57.2	61.6	66.0	121.0	132.0	143.0	154.0	165.0
23	50.6	55.2	59.8	64.4	69.0	126.5	138.0	149.5	161.0	172.5
24	52.8	57.6	62.4	67.2	72.0	132.0	144.0	156.0	168.0	180.0
25	55.0	60.0	65.0	70.0	75.0	137.5	150.0	162.5	175.0	187.5

For example, if 2 tons of crop residues containing 0.47 C are applied to a soil in a mild moist climate (where soil C sequestration = 0.12), then the soil C gain at the end of the first year is calculated as:

Soil C sequestration (after one year)= 2.0 t ha^{-1} x 0.47t C t^{-1} x 0.12 t soil C t^{-1}) = 0.11 t C

This relationship demonstrates that the soil C gain is relatively small compared to the amount of soil C inputs. Furthermore, the "young" soil C continues to decompose over time. Assuming that the soil carbon gain belongs to a labile carbon pool with a turnover of 0.2 per years (≈ 5 years, see Woomer *et al*., 1994; Parton *et al*., 1994), then the C remaining over time may be described as soil C remaining = soil C sequestration x (1 – turnover)^{time} or, in the case above (for 2 t of crop residue) at the end of 4 years (3 more years)

Soil C sequestration = 2.0 t ha^{-1} x 0.47t C t^{-1} x 0.12 t soil C t^{-1}) x (0.8)^3 = 0.06 t C

This sort of C gain is extremely modest and, assuming that C is valued for $10 per ton, extremely difficult to document in a cost effective manner given the cost of soil C analyses.

Table 4. Soil carbon gains (tons) after one year resulting from either the application (left) or return (right) of crop residues with different climate-driven carbon sequestration efficiencies. Applied assumes that residues are transported elsewhere, returned assumes that crop roots also contribute C.

	climate					climate				
crop residue	cool dry		mild moist		hot humid	cool dry		mild moist		hot humid
	soil C sequestration efficiency									
	20%	16%	12%	10%	6%	20%	16%	12%	10%	6%
(kg)	kg C from crop residue applied					kg C from crop residue returned				
250	0.02	0.02	0.01	0.01	0.01	0.03	0.03	0.02	0.02	0.01
500	0.05	0.04	0.03	0.02	0.01	0.06	0.05	0.04	0.03	0.02
750	0.07	0.06	0.04	0.04	0.02	0.10	0.08	0.06	0.05	0.03
1000	0.09	0.08	0.06	0.05	0.03	0.13	0.10	0.08	0.06	0.04
1250	0.12	0.09	0.07	0.06	0.04	0.16	0.13	0.10	0.08	0.05
1500	0.14	0.11	0.08	0.07	0.04	0.19	0.15	0.11	0.10	0.06
1750	0.16	0.13	0.10	0.08	0.05	0.22	0.18	0.13	0.11	0.07
2000	0.19	0.15	0.11	0.09	0.06	0.25	0.20	0.15	0.13	0.08
2250	0.21	0.17	0.13	0.11	0.06	0.29	0.23	0.17	0.14	0.09
2500	0.24	0.19	0.14	0.12	0.07	0.32	0.25	0.19	0.16	0.10
2750	0.26	0.21	0.16	0.13	0.08	0.35	0.28	0.21	0.17	0.10
3000	0.28	0.23	0.17	0.14	0.08	0.38	0.30	0.23	0.19	0.11
3250	0.31	0.24	0.18	0.15	0.09	0.41	0.33	0.25	0.21	0.12
3500	0.33	0.26	0.20	0.16	0.10	0.44	0.36	0.27	0.22	0.13
3750	0.35	0.28	0.21	0.18	0.11	0.48	0.38	0.29	0.24	0.14
4000	0.38	0.30	0.23	0.19	0.11	0.51	0.41	0.30	0.25	0.15
4250	0.40	0.32	0.24	0.20	0.12	0.54	0.43	0.32	0.27	0.16
4500	0.42	0.34	0.25	0.21	0.13	0.57	0.46	0.34	0.29	0.17
4750	0.45	0.36	0.27	0.22	0.13	0.60	0.48	0.36	0.30	0.18
5000	0.47	0.38	0.28	0.24	0.14	0.63	0.51	0.38	0.32	0.19
5250	0.49	0.39	0.30	0.25	0.15	0.67	0.53	0.40	0.33	0.20
5500	0.52	0.41	0.31	0.26	0.16	0.70	0.56	0.42	0.35	0.21
5750	0.54	0.43	0.32	0.27	0.16	0.73	0.58	0.44	0.36	0.22
6000	0.56	0.45	0.34	0.28	0.17	0.76	0.61	0.46	0.38	0.23
6250	0.59	0.47	0.35	0.29	0.18	0.79	0.63	0.48	0.40	0.24
6500	0.61	0.49	0.37	0.31	0.18	0.82	0.66	0.49	0.41	0.25
6750	0.63	0.51	0.38	0.32	0.19	0.86	0.69	0.51	0.43	0.26
7000	0.66	0.53	0.39	0.33	0.20	0.89	0.71	0.53	0.44	0.27
7250	0.68	0.55	0.41	0.34	0.20	0.92	0.74	0.55	0.46	0.28
7500	0.71	0.56	0.42	0.35	0.21	0.95	0.76	0.57	0.48	0.29
7750	0.73	0.58	0.44	0.36	0.22	0.98	0.79	0.59	0.49	0.30
8000	0.75	0.60	0.45	0.38	0.23	1.02	0.81	0.61	0.51	0.30
8250	0.78	0.62	0.47	0.39	0.23	1.05	0.84	0.63	0.52	0.31
8500	0.80	0.64	0.48	0.40	0.24	1.08	0.86	0.65	0.54	0.32
8750	0.82	0.66	0.49	0.41	0.25	1.11	0.89	0.67	0.56	0.33
9000	0.85	0.68	0.51	0.42	0.25	1.14	0.91	0.69	0.57	0.34
9250	0.87	0.70	0.52	0.43	0.26	1.17	0.94	0.70	0.59	0.35
9500	0.89	0.71	0.54	0.45	0.27	1.21	0.96	0.72	0.60	0.36
9750	0.92	0.73	0.55	0.46	0.27	1.24	0.99	0.74	0.62	0.37
10000	0.94	0.75	0.56	0.47	0.28	1.27	1.02	0.76	0.63	0.38
10250	0.96	0.77	0.58	0.48	0.29	1.30	1.04	0.78	0.65	0.39
10500	0.99	0.79	0.59	0.49	0.30	1.33	1.07	0.80	0.67	0.40
10750	1.01	0.81	0.61	0.51	0.30	1.36	1.09	0.82	0.68	0.41
11000	1.03	0.83	0.62	0.52	0.31	1.40	1.12	0.84	0.70	0.42
11250	1.06	0.85	0.63	0.53	0.32	1.43	1.14	0.86	0.71	0.43
11500	1.08	0.86	0.65	0.54	0.32	1.46	1.17	0.88	0.73	0.44
11750	1.10	0.88	0.66	0.55	0.33	1.49	1.19	0.89	0.75	0.45
12000	1.13	0.90	0.68	0.56	0.34	1.52	1.22	0.91	0.76	0.46

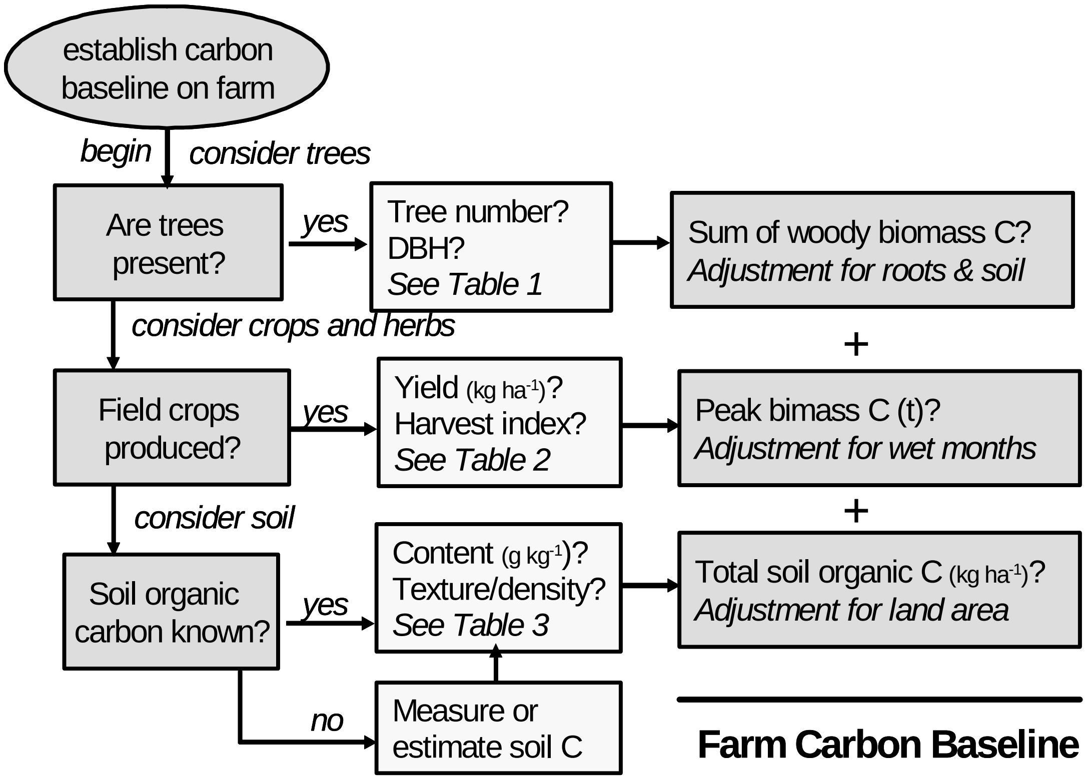

Figure 2. A stepwise approach to establishing a farm carbon baseline that considers trees, crops and soil that may be adjusted to different land areas.

Table 4 presents the soil C gain after one year resulting from different sized residue additions in various climates. The figures to the left assume that the residues are repositioned (transported and applied) and the figures to the right assume that crop residues are incorporated in the field from which they originate, including crop roots. Carbon sequestration efficiencies may be interpolated across columns depending on climatic conditions and, the effects are additive so that sequestration resulting from a 20 t addition of returned residues is equal to that resulting from 10 t x 2, or 1.26 t in a mild humid climate (0.63 x 2). This table does not take chemical characteristics into account. In general, organic residues with a low C:N ratio and low in lignin and polyphenol decompose more rapidly and completely than those low in nitrogen and high in recalcitrant, secondary compounds. Again, it is advised that Table 4 be applied with caution as the difficulties in actually documenting the soil carbon claims are much more difficult than those in biomass.

A shortcut approach. Lengthy mathematical discussion of these tables may distract from their overall purpose, to allow for rapid and accurate estimation of woody biomass and soil carbon stocks based upon minimum information. Carbon stocks which could not be "visualized" by land managers, development specialists or extensionists may now be quantified using these tables (Figure 2). Take for example the carbon gain due to an improved tree fallow producing 1000 trees per ha of 15 cm diameter and that increased total soil organic carbon in the loam by 0.8% C. The woody biomass gain per ha is 0.033 t x 1000 = 33 t ha-1. The soil C gain (for 8 g C per kg soil) is 35.2 t C ha, yielding a system C optima of 68.2 t C ha. This value is best adjusted over time. If the fallow interval is five years, the C sequestration rate for woody biomass and total system C is 6.6 and 13.6 t $ha^{-1}yr^{-1}$, respectively.

It must be emphasized that these tables that are intended to assist a wider cross-section of the land management and environmental communities to become involved in the estimation of carbon stocks and agro-biodiversity, and in some ways are over-simplified. Table 1 is based upon a preliminary assumption of a single widely applicable allometric equation predicting aboveground tree biomass and this table could be better refined for more applicable DBH size categories and different tree species and vegetation zones. Table 2 presents yield increments of 500 kg and assumes that one is aware of the harvest index for a given crop. Table 3 assumes that the range of interest for soil C stocks is 25 g C kg soil^{-1} and that five textures adequately cover the range of soil texture conditions. Total system C estimates derived from combining these three somewhat speculative because assumptions about root biomass and annual litter turnover are also taken into account.

Figure 2 illustrates how to use this information in this chapter to estimate the carbon in a field or on your farm. To do this, one must know the number of trees and their diameters, crop yields and have an estimate of the harvest index, the soil organic C content and the soil bulk density. Get a paper and pencil (or a good calculator) and then refer to Table 6 to compile a farm or field carbon baseline, the carbon gains from tree planting and the value of that carbon. Table 6 is completed using the following procedure:

1. Step 1. Establish baseline: tree biomass C. This section of the form is intended for completion before the initiation of a carbon offset project, or may be completed by comparing a cropland adjacent to tree planting, assuming that the land use and soil are representative. Enter the DBH and number of trees that fall into up to three different size categories and refer to Table 1a to identify the tree biomass C for each category by matching the tree diameter (columns) and number of trees (rows). Additional categories may be included on a separate sheet if necessary. Sum the categories to obtain the Total Tree Biomass and enter this value into the far right column of Table 5.
2. Step 1. Crop Biomass C. Enter the yield and harvest index for up to two crops grown either sequentially within the same year or as intercrops. And identify the peak C for each by matching the harvest indices (columns) and crop yield (rows) from Table 2. Sum these values to obtain the Total peak Crop C and enter this value into the far right column of Table 5. Time-average this value by including the total number of wet months.
3. Step 1. Soil C. This section requires that the soil be analyzed to C and the results expressed as g C per kg soil (= 0.1 x C %). Based on either soil texture or bulk density, identify the appropriate column and match this with the appropriate C content in Table 3 to obtain the value for total soil C (t C per ha) and enter it into the far right column of Table 5.
4. Step 1. Total system baseline C. Calculate this value as the sum of total tree, time-averaged crop and soil C and enter it into the far right column. This value is the baseline C.
5. Step 2. Project C gains: Tree and Soil C. This part of the form is intended to be completed at regular intervals (e.g. once a year) after the planted trees are established and growing. Enter the tree numbers and diameters and identify their C contents, this time using Table 1b, which also considers C gain in the soil beneath the trees.
6. Step 2. Intercrop C. Include the time-averaged C content contained in intercrops (Table 2), understorey or cover crops and adjust the value by wet months. Many cover crops lack "yield" so the biomass C must be obtained through destructive sampling (see next section).
7. Step 2. Project C gains. Sum the tree and crop C values; this is the unadjusted Total project C gain.
8. Step 3. Net project C gain. Calculate this value by subtracting the baseline value, but do not include the baseline soil C (baseline tree and crop C, but not soil C) and enter in the far right column. Calculate the value of this C by multiplying it by the C price, usually $10 per t C.

Table 5. Calculating C baseline, project C gains and carbon

Step 1: Establish baseline C status in project area

Tree biomass C (from Table 1a)

Tree category 1 DBH _________ number __________ carbon _________________

Tree category 2 DBH _________ number __________ carbon + _______________

Tree category 3 DBH _________ number __________ carbon + _______________

Total tree biomass C (TTBC) = ∑ categories 1-3 **= _____________ t C**

Crop biomass C (from Table 2)

Crop 1 _______________ yield ______ harvest index _____ peak C _________________

Crop 2 _______________ yield ______ harvest index _____ peak C + _______________

Total peak crop C (TPCC) = ______________ t C

Time-averaged crop C (TACC) = (0.5 x (TPCC)) / (12 – wet months) = **______________ t C**

Soil C (from Table 3)

Soil carbon content (g C kg^{-1} soil) _________ _

Texture _________________ or bulk density ___________ kg l^{-1}

Soil depth [} 20 cm [} 50 cm) Soil C (from Table 3) ______________ t ha^{-1}

Land area ________________ ha

Total soil C (TSC) = Soil C (t ha^{-1}) / land area (ha) = **______________ t C**

Total system baseline C (TSBC) = TTBC + TACC + TSC = ______________ t C

Step 2: Estimate C project gains through tree planting and intercropping

Tree biomass and soil C gains (from Table 1a)

Tree category 1 DBH _________ number __________ carbon _________________

Tree category 2 DBH _________ number __________ carbon + _______________

Tree category 3 DBH _________ number __________ carbon + _______________

Total tree and soil C gains (TSCG) = ∑ categories 1-3 **= _______________ t C**

Intercrop biomass C (from Table 2)

Intercrop 1 ______________ yield ______ harvest index _____ peak C _________________

Intercrop 2 ______________ yield ______ harvest index _____ peak C + _______________

Total peak crop C (TPCC) = _____________ t C

Time-averaged crop C gain (TACG) = (0.5 x (TPCC)) / (12 – wet months) = **_____________ t C**

Total project C gain (TPCG) = TSCG + TACG = _____________ t C

Step 3: Calculate net project C and value

Net project C (NPC) = (TPGC – (TSBC – TSC))

TPGC _______________ t C

TSBC - _____________ t C

TSC - _____________ t C

NPC = _____________ t C

Net Project C value = Net project C (t) x C price ($ t^{-1})

C price ($ t^{-1}) x _____________ $ t^{-1}

Net Project C value = _____________ $

Verifying Carbon: Detailed Field Procedures

Project researchers may require more precise estimates of total system carbon in order to ground truth remotely-sensed data or to calibrate the shortcut method based upon tabular-based estimates in the Visualize Carbon section (above). The approach described below is based upon Woomer et al. (2001) for smallhold farms and Woomer and Palm (1998) for forests, readers' detailed field procedures are referred to those papers. The model for total system C is:

Total C = AG tree C + AG herbaceous C + root C + litter C + soil C

Tree C is based upon allometric equations published by FAO (1997). Herbaceous C refers to either field crops, forest understorey of small trees and shrubs. Roots may either be excavated or estimated based upon known root:shoot ratios. Surface litter is gathered from small quadrates and soil C is measured, in this case, by dry combustion. Keep in mind that these field procedures are time and labour demanding, and it is difficult to document C gains within a complex agroecosystem at less expense than the value of those gains. Nonetheless, it is important that standardized field procedures be developed for the project so that the detailed carbon measurements collected during the project are more comparable.

Teams and Tools

Tools for characterizing carbon pools.

A minimum of three team members are required to conduct these field procedures, one of which is designated the leader and held responsible for all randomization procedures, data entry protocols and sample labelling codes. These methods, however, are most efficiently conducted by teams of eight consisting of a leader, three members establishing major quadrates and measuring tree diameters followed by two members positioning understorey sub-quadrates and recovering vegetation and litter followed by two members sampling soils and recovering roots. Local land managers who wish to work with the team should not be discouraged but require initial supervision and cautioning about site disturbance prior to and during measurements. Transporting samples from remote sites to road heads is often very labour and time demanding and teams must adjust their pace to this end-of-day effort. One option is to begin measurements furthest from the road head in the morning and work towards it during the day. A list of field equipment useful in conducting carbon measurements is presented in Table 6. Most of this equipment is readily available in developing countries with the exception of geographical positioning systems, range finders and hand saws suitable for cutting roots in the soil.

Table 6. Important field tools and their uses in a field campaign to measure total system carbon in smallhold farming systems.

tool: use

geographic positioning system: identify geographic coordinates of site and land use
local or aerial map: assist in site location, establish rapport with farmers
random number table: assist in randomization decisions
compass: assist in mapping and randomization direction
data sheets and clip board: enter DBH and labelling codes with sketch maps on reverse side
range finder: measure farm and field dimensions
metric tape measure: establish 50 m linear axis of major quadrat. Measure field dimensions
diameter tape: measure tree diameter
fluorescent tape: mark approximate location of major quadrates
dial calliper: measure DBH of smaller trees
1 m x 1 m wooden quadrat: establish boundaries for understorey recovery
0.5 m x 0.5 m wooden quadrat: establish boundaries for surface litter recovery
hand shears: recover understorey vegetation
small hand rake: recover surface litter
hand saw: recover small trees, woody litter and larger roots
flat-bladed shovel: excavate soil and roots
bulk density cylinders: recover soil bulk density samples for each land use
wooden mallet: drive bulk density cylinders into soil
flat-bladed knife: trim soil cylinders and others
camera and film: document procedures and land uses
plastic tarp: establish sample processing area

Woody Biomass Carbon Measurement and Sampling


Measuring tree diameter with a diameter tape (above, left) and calipers (below, right).

The presence and arrangement of woody biomass governs the approach to aboveground carbon measurement within an ecosystem (Woomer and Palm, 1998; Woomer *et al*., 2000). Trees in remnant forests and in farmers' fields and woodlots be measured within replicated plots (e.g. 30 m x 30 m) with the location established through a stratified, random process. This approach is poorly applicable to situations where trees are infrequent or dispersed, in which case the plot size must either be increased or line transects established (Woomer *et al*., 2001). An alternative approach, The Point-Quarter Sampling Technique (Brower *et al*., 1990; Sutherland, 1996) relies on plotless sampling for tree or shrub density, biomass, or related properties and is often the method of choice when individuals are sparse and widely separated and it is too laborious to use line or belt transects. Systematically planted trees are measured along rows with the transect width adjusted to the inter-row spacing. Trees and large shrubs within boundaries are measured in similar fashion with the transect width also adjusted to conditions.

The diameter at breast height (DBH in cm) of all stems greater than 2 cm is recorded using callipers or a diameter tape where circumference is expressed in units of diameter. Biomass is assigned to individual trees through allometric equations either empirically derived from local conditions or adopted from previous work in various ecological zones (Brown *et al.*, 1989; FAO, 1997). Allometric equations based upon power functions, which intercept the origin, are recommended above quadratic approaches because of their greater accuracy for assigning biomass to smaller trees. For general purposes, we recommend the equations from FAO (1997) in Dry Zones (<1500 mm y^{-1}):

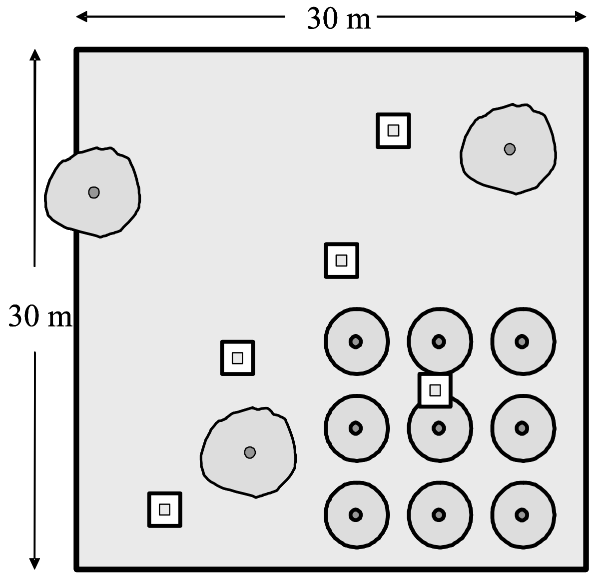

Figure 3. The sampling approach for woody biomass estimation with sub-quadrates for understorey, litter and soil/root sampling. Note that the 1.0 m^2 understorey sub-quadrat is nested within the 900 m^2 major quadrat. R indicates randomization decisions.

$$\textit{Aboveground tree biomass (kg tree}^{-1}\textit{)} = exp^{(-1.996 + 2.32\ lnD)}$$

and in Moist Zones (1500-4000 mm y^{-1}):

$$\textit{Aboveground tree biomass (kg tree}^{-1}\textit{)} = exp^{(-2.134 + 2.53\ lnD)}$$

where Y is the aboveground tree biomass in kg and D is the measured DBH in cm. Other equations are available for drier (<900 mm y^{-1}) and wet zone (>4000 mm y^{-1}) from FAO (1997). The above equations are based upon lowland tropical moisture-temperature relationships and judgement is required when applying them to higher elevations as evapotranspiration decreases and climate becomes "wetter" at a given rainfall (FAO, 1997). Tree biomass is converted to carbon by a factor of 0.47 and various rules are applied toward leaning, fallen and heavily branched trees (Woomer and Palm, 1998). The average biomass (kg) of field-replicated 900 m^2 plots (Figure 3) is adjusted to Mg ha^{-1} with a factor of 0.011 (10000 m^2 ha-1 / 900 m^2 plot-1 / 1000 kg Mg^{-1}).

During the baseline study, the plot size for C measurement was a randomly-selected area of 30 m x 30 m (= 900 m^2) as presented in Figure 3. The DBH of all trees with trunks falling within that area were recorded, and then five understorey quadrates deployed at random within the main plot for destructive sampling of shoots, litter and roots and the recovery of soils. A table of random numbers useful for placement of sampling quadrates appears in Appendices 2 & 3. The procedure relied upon during the baseline study is likely too expensive and time consuming to be relied upon for routine monitoring of C stocks, but it does serve as an example for the verification of estimates developed using the shortcut method previously described. For example, it is suitable for lands with randomly and systematically placed trees.

Herbaceous and Surface Litter Carbon Sampling and Measurement

Herbaceous and woody vegetation with DBH less than 2.5 cm is harvested from randomized (see Appendix 1), replicated 1.0 m x 1.0 m frames (Figure 1). Transects are laid in each farm enterprise and 1.0 m^2 quadrat positions assigned at random intervals along them (Appendix 1B). The quadrates may be "nested" within the 100 m^2 tree quadrates, or when trees are absent or sparse, located independently of tree measurement. Plant tissues originating outside of the quadrat but falling within it are recovered and plant tissues originating within the quadrat but grown beyond it are discarded. Then all remaining vegetation is cut at ground-level and recovered. Care is taken to collect any fresh tissues that fall during harvest. Samples are weighed, sub-sampled, dried at 65° C to constant weight and corrected for moisture. Live vegetation is assumed to contain 0.45 C once dried. The average biomass (kg) of field-replicated 1.0 m^2 herbaceous quadrates is adjusted to Mg ha^{-1} with a factor of 10 (10000 quadrates ha^{-1}/1000 kg Mg^{-1}). Measurement of annual crop biomass is time consuming considering the size of their carbon stocks. An alternative approach is to reconstruct biomass C by adjusting yields with harvest index and the proportion of roots using the equation:

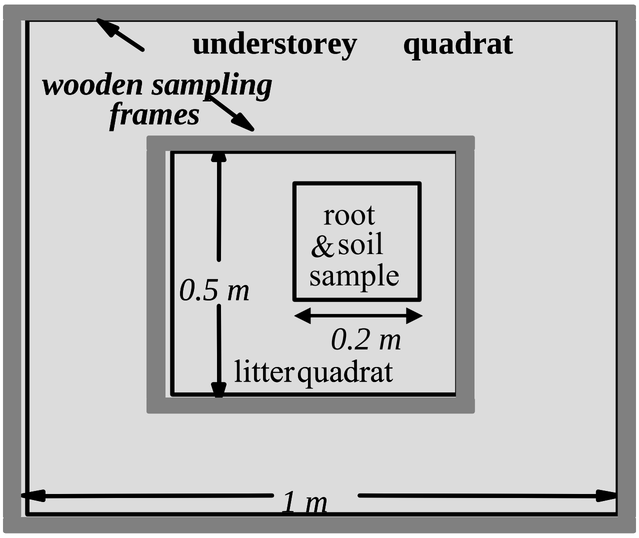

Figure 4. The sampling areas for understorey biomass (1 m^2) surface litter (0.25 m^2) and roots and soil (0.04 m^2 to a depth of 40 cm).

$$\textit{Biomass C (Mg ha}^{-1}\textit{)} = 0.45 \times ((CY/HI) + RR(CY/HI))$$

where CY = reported average crop yield, HI = harvest index and RR = the ratio of below-ground to aboveground biomass. This equation forms the basis for the peak crop biomass C estimates presented in Table 2.

Surface litter is collected from centrally-positioned 0.5 m x 0.5 m frames within the larger herbaceous vegetation quadrates using a small hand rake (Figure 1). Surface litter is assumed to be necromass of identifiable origin (e.g. leaves, fine branches) although judgement is often necessary in differentiating it from the soil organic horizon in grasslands or under trees. Woody necromass <10 cm in diameter falling within the 0.25 m^2 quadrat is collected with a hand saw. Logs >10 cm diameter require separate characterization based upon geometric and wood density approaches (Woomer and Palm, 1998). Surface litter is washed over a 2 mm sieve, dried at 65° C to constant weight and corrected for moisture. Alternatively, the litter is sub-sampled and ashed in a muffle

Understorey and litter quadrates are randomly placed along a transect furnace to remove mineral contaminants. Once dried or combusted, surface litter is assumed to contain 0.45 C. The average biomass (kg) of field-replicated 0.25 m^2 surface litter quadrates is adjusted to Mg ha^{-1} with a factor of 40 (40000 quadrates ha^{-1}/1000 kg Mg^{-1}). Measurement of surface litter is not time consuming but this carbon stock tends to be small in enterprises other than woodlots, perennial crops, fodders and fallows.

Belowground Carbon: Roots and Soil

Root measurement is a necessary component of detailed investigations comparing candidate management interventions but is too time consuming for purposes of routine monitoring. Roots are collected by excavating an area 0.2 m x 0.2 m to a depth of 30 cm with a narrow, flat-bladed shovel and hand saw. Coarse roots are hand sorted and washed. The remaining sample is dispersed in tap water, passed through a 2 mm sieve and roots collected without attempt to differentiate live and dead roots. Roots are then washed of gross mineral contamination, dried at 65^o to constant weight, weighed and a sub-sample ground and ashed. Ash-corrected dry weight is assumed to contain 0.45 carbon. The average biomass (kg) of field-replicated 0.04 m^2 root quadrates is adjusted to Mg ha^{-1} with a factor of 250 (250000 quadrates ha^{-1}/1000 kg Mg^{-1}). Other methods of sampling root biomass are described by Anderson and Ingram (1993).

An alternative approach is to assign root biomass as a proportion of aboveground biomass. While a paucity of information is available on the proportion of roots in many tropical ecosystems, one estimate from Senegal may prove useful to researchers in African drylands. The proportion of roots to woody biomass was calculated to be 0.38 based upon the work of Bille and Poupon (1972) who had examined subterranean tree biomass for 17 trees of up to 27 cm diameter.

Soils are recovered in two increments of 0-30 cm using a narrow, flat-bladed shovel or soil auger. Care is taken to recover coarse roots using a small hand saw during the excavation. Samples for soil bulk density are recovered by driving a thin-walled metal cylinder of known volume into the vertical face of the excavation with a wooden mallet at two depths (10 cm and 35 cm, one central to each incremental soil sample), withdrawing the filled cylinder, trimming soil protrusions with a knife and storing the sample in a plastic bag for later soil moisture and bulk density determination. Chemical analyses for soil and litter carbon are described in the following section.

Soil samples are passed through a 0. 3 mm sieve prior to analysis of the organic carbon content by dry combustion. Standard operating procedures for the ThermoQuest.CN analyzer are followed during the analysis of soil samples. Oxygen is the combustion gas, helium the carrier gas and compressed medical air used for purging. The combustion furnace temperatures are 900^0C (the reactor tube is held inside this furnace). The sample weights used are between 18 mg and 22 mg. A standard and a blank tin capsule are run after every 10 samples. Detection of carbon is through change in thermal conductivity measured by a TCD detector thermal conductivity detector installed within the CN analyzer

Data Compilation, Analysis and Interpretation

To calculate total system carbon stocks, the individual carbon pools, woody biomass, herbaceous biomass, litter, roots and soil, are totalled and expressed as kg or Mg carbon ha^{-1} (Woomer and Palm, 1998; Woomer *et al*., 2000). This operation is best performed within a spreadsheet data base by entering the carbon pools as columns and the sites (cases) as rows. Additional columns are required that characterize the site in terms of its coordinates, land use, soil characteristics and additional references. An extract from such a data base that is being constructed for sites in Senegal appears in Table 2. Completion of the spreadsheet C data base allows for similar sites to be grouped, and summary statistics performed. Data for one set of carbon values obtained for a given zone and land use combination may be compared to other sets through estimates of error terms.

Approaches to estimating biomass and wood volumes within different farm enterprises are presented in Table 7. Annual crops should be measured at peak biomass or biomass data is better reconstructed from yield records. Banana presents a problem in biomass measurement. It is a giant herb with a large underground storage organ. The application of allometric equations for woody biomass is inappropriate and destructively sampling bananas as herbaceous biomass is extremely difficult. Modelling approaches may assist in reconstructing banana biomass C from yield records when detailed soil data is available and land history known (Woomer *et al.*, 1997, 2001). Younger fallows and woodlots are undergoing successional changes and researchers must exercise judgement in randomization procedures, particularly for woody biomass measurement (Woomer and Palm, 1998). An alternative to DBH for large shrubs is to calculate the shrub bio-volume (= cover x height) and assign a calibrated biomass C density factor (e.g. about 0.2 kg C m^3. Fields of annual crops and fodder often contain scattered trees, the DBH of each should be measured as these may contain greater biomass than the crop. It may be necessary to separate farm and field boundaries because the former usually contains more and larger trees, requiring a set of total length, average width and unit biomass measurements for each. Guidelines for estimating wood volume of farm structures are not well established but information is available on the density of wood from many tree species (FAO, 1997).

Table 7. Approaches to estimating biomass and wood volumes in different enterprises of smallhold farming systems.

Farm enterprise	Approach
Annual food crops	Measure random sample of herbaceous vegetation by destructive sampling of small quadrates with plot size dependent upon row spacing. Include scattered woody biomass by measuring DBH >2.5 cm. Crop biomass may be reconstructed from yield through harvest index. Adjust for cropping pattern.
Woodlots and perennial crops	Calculate total row length of woody biomass. Measure DBH of a random sample of trees >2.5 cm in 25 m long quadrates with rows adjusted for row spacing. Adjust randomization procedures in woodlots resembling natural forest.
Annual market crops	Destructively sample herbaceous vegetation in randomized, replicated 1.0 m^2 quadrates or reconstruct biomass based on yields.
Fodder, forage and fallow	Destructively sample herbaceous vegetation in randomized, replicated 1.0 m^2 quadrates. Count and measure DBH of scattered trees. Tree fallows are considered woodlots.
Farm and field boundaries	Establish total length and average width of farm boundaries. Measure DBH of woody vegetation >2.5 cm along randomized, replicated 25 m sections. Nest quadrates for destructively sampled herbaceous vegetation within woody biomass sample if necessary.
Household area	Estimate the wood volume of structures and adjust for wood density. Measure DBH of woody biomass >2.5 cm. Estimate mass of manure piles and compost, sample and analyze for total C. Include fences and other wooden structures.

Literature Cited

Beenje, H.J. 1994. *Kenya Trees, Shrubs and Lianas*. National Museums of Kenya, Nairobi. 722 pp.

Bille, J.C. and Poupon, H. 1972. Recherches Ecologiques sur une savane sahélienne du Ferlo septentroional, Senegal: biomasse végétale et production primaire nette. *Revue d'Ecologie Appliquée* 26:366-382.

Boulinier, T., Nichols,, J.D., Sauer, J.R., Hines, J.E. and Pollock, K.H. 1998. Estimating species richness: the importance of heterogeneity in species detectability. *Ecology* 79:1018-1028.

Food and Agriculture Organization of the United Nations (FAO). 2000. *Carbon Sequestration Options Under the Clean Development Mechanism to Address Land Degradation*. FAO World Soil Resources Reports No. 92. Rome. 36 pp.

Food and Agriculture Organization of the United Nations (FAO). 1997. *Estimating Biomass and Biomass Change of Tropical Forests: A Primer*. FAO Forestry Paper 134. FAO, Rome. 55 pp.

Gotelli, N.J. and Colwell, R.K. 2001. Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. *Ecology Letters* 4:379-391.

International Centre for Research in Agro-Forestry (ICRAF). 1992. Useful Trees and Shrubs of Kenya. ICRAF, Nairobi.

Kapkiyai, J., Woomer, P.L., Qureshi, J., Smithson, P. and Karanja, N. 1999. Soil organic matter and nutrient dynamics in a Kentan nitisol under long-term fertilizer and organic input management. *Soil Biology and Biochemistry* 31:1173-1782.

Kindt, R. 2002. The Biodiversity Analysis Package.: Resources and guidelines for the analysis of biodiversity and ecological information (Compact Disk).Version 1. World Agroforestry Centre, Nairobi, Kenya

Ketterings, Q.M., Coe, R., van Noordwijk, M., Ambangau, Y. and Palm, C.A. 2001. Reducing uncertainty in the use o allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. *Forest Ecology and Management* 146:199-209.

Magnussen, S., and Boyle, T.J.B. 1995. Estimating sample size for inference about the Shannon-Weaver and the Simpson indices of species diversity. *Forest Ecology and Management* 78: 71-84.

Maundu, P.M., Ngugi, G.W. and Kabuye, C.H.S. 1999. *Traditional Food Plants of Kenya*. Kenya Resource Centre for Indigenous Knowledge, National Museums of Kenya, Nairobi. 270 pp.

Metherell, A.K., Harding, L.A., Cole, C.V. and Parton, W.J. 1993. *Century Organic Matter Model Environment: Technical Documentation,* Agroecosystem Version 4.0. Great Plains System Research Unit, Technical Report No. 4. USDA-ARS Fort Collins, Colorado

Noble, I. and Scholes, R.J. 2001. Sinks and the Kyoto Protocol. *Climate Policy* 1:5-25

Okalebo, J.R., Gathua, K.W. and Woomer, P.L. 2002. *Laboratory Methods of Soil and Plant Analysis: A Working Manual.* Second Edition. TSBF-CIAT and SACRED Africa, Nairobi. 128 pp.

Parton, W.J., Woomer, P.L. and Martin, A. 1994 Modelling soil organic matter dynamics and plant productivity in tropical ecosystems. In: Woomer PL, Swift MJ (eds.) The Biological Management of Tropical Soil Fertility. J. Wiley & Sons, Chichester, UK. p 171-189

Purvis, A., and A. Hector. 2000. Getting the measure of biodiversity. Nature 405: 212-218.

Simons, A.J. 2003. Principles and Criteria for Carbon Offset Enterprises in Smallholder Agroforestry (Draft). World Agroforestry Centre, Nairobi (7 pp. in-house document).

Shepherd, K.D. and Soule, M.J. 1998. Soil fertility management in west Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. Agriculture, Ecosystems and Environment 71:131-145.

Trexler, M.C. 1993. Manipulating biotic carbon sources and sinks for climate change mitigation: can science keep up with practice? Water Air and Soil Pollution 70:579-593.

Tyndall, B. 1996. The Socioeconomics of Grevillea robusta within the coffee land-use system of Kenya.AFRENA Report No. 109. ICRAF, Nairobi. 71pp.

White F 1983 Chapter XII. The Lake Victoria Regional Mosaic. In: *The Vegetation of Africa*. UNESCO, Paris. p 179-184.

Woomer, P.L. and Palm, C.A. 1998. An approach to estimating system carbon stocks in tropical forests and associated land uses. Commonwealth Forestry Review 77:181-190.

Woomer, P.L., Karanja, N.K. and Murage, E.W. 2001. Estimating total system C in smallhold farming systems of the East Africa Highlands. Assessment Methods for Soil Carbon (R. Lal, J.M. Kimble, R.F. Follett and B.A. Stewart, eds.), Advances in Soil Science (series). Lewis Publishers, Boca Raton, USA. pp. 147-166.

Woomer, P.L., Palm C.A., Qureshi, J.N. and Kotto-Same J. 1997. Carbon sequestration and organic resource management in African smallholder agriculture. In: R. Lal, J.M. Kimble, R.F. Follett and B.A. Stewart (eds.) *Management of Carbon Sequestration in Soils*. *Advances in Soil Science*, CRC Press, Florida. pp. 58-78.

Appendix 1. Estimates of tree C in aboveground biomass resulting from tree biomass of different diameters using the equation AGB C = 0.47 x $\exp^{(-1.997 + 2.32 (\ln DBH))}$. Unlike Table 1, this table does not consider root biomass or soil C gains.

tree	DBH (cm)																
number	5	7.5	10	12.5	15	20	25	30	35	40	45	50	60	70	80	90	100
	aboveground tree biomass C (tons)																
1	0.00	0.01	0.01	0.02	0.03	0.07	0.11	0.17	0.24	0.33	0.44	0.56	0.85	1.22	1.66	2.18	2.79
2	0.01	0.01	0.03	0.04	0.07	0.13	0.22	0.34	0.49	0.67	0.87	1.12	1.70	2.44	3.32	4.37	5.58
3	0.01	0.02	0.04	0.07	0.10	0.20	0.34	0.51	0.73	1.00	1.31	1.67	2.56	3.66	4.98	6.55	8.36
4	0.01	0.03	0.05	0.09	0.14	0.27	0.45	0.68	0.98	1.33	1.75	2.23	3.41	4.87	6.64	8.73	11.15
5	0.01	0.03	0.07	0.11	0.17	0.33	0.56	0.85	1.22	1.66	2.19	2.79	4.26	6.09	8.31	10.92	13.94
6	0.02	0.04	0.08	0.13	0.21	0.40	0.67	1.02	1.46	2.00	2.62	3.35	5.11	7.31	9.97	13.10	16.73
7	0.02	0.05	0.09	0.16	0.24	0.47	0.78	1.19	1.71	2.33	3.06	3.91	5.97	8.53	11.63	15.28	19.51
8	0.02	0.05	0.11	0.18	0.27	0.53	0.89	1.37	1.95	2.66	3.50	4.47	6.82	9.75	13.29	17.47	22.30
9	0.02	0.06	0.12	0.20	0.31	0.60	1.01	1.54	2.20	2.99	3.93	5.02	7.67	10.97	14.95	19.65	25.09
10	0.03	0.07	0.13	0.22	0.34	0.67	1.12	1.71	2.44	3.33	4.37	5.58	8.52	12.19	16.61	21.83	27.88
11	0.03	0.08	0.15	0.25	0.38	0.73	1.23	1.88	2.68	3.66	4.81	6.14	9.37	13.40	18.27	24.01	30.66
12	0.03	0.08	0.16	0.27	0.41	0.80	1.34	2.05	2.93	3.99	5.25	6.70	10.23	14.62	19.93	26.20	33.45
13	0.03	0.09	0.17	0.29	0.44	0.87	1.45	2.22	3.17	4.32	5.68	7.26	11.08	15.84	21.60	28.38	36.24
14	0.04	0.10	0.19	0.31	0.48	0.93	1.57	2.39	3.42	4.66	6.12	7.82	11.93	17.06	23.26	30.56	39.03
15	0.04	0.10	0.20	0.34	0.51	1.00	1.68	2.56	3.66	4.99	6.56	8.37	12.78	18.28	24.92	32.75	41.82
16	0.04	0.11	0.21	0.36	0.55	1.07	1.79	2.73	3.90	5.32	7.00	8.93	13.64	19.50	26.58	34.93	44.60
17	0.05	0.12	0.23	0.38	0.58	1.13	1.90	2.90	4.15	5.66	7.43	9.49	14.49	20.72	28.24	37.11	47.39
18	0.05	0.12	0.24	0.40	0.62	1.20	2.01	3.07	4.39	5.99	7.87	10.05	15.34	21.94	29.90	39.30	50.18
19	0.05	0.13	0.25	0.43	0.65	1.27	2.12	3.24	4.64	6.32	8.31	10.61	16.19	23.15	31.56	41.48	52.97
20	0.05	0.14	0.27	0.45	0.68	1.33	2.24	3.41	4.88	6.65	8.74	11.17	17.04	24.37	33.22	43.66	55.75
30	0.08	0.21	0.40	0.67	1.03	2.00	3.35	5.12	7.32	9.98	13.12	16.75	25.57	36.56	49.84	65.50	83.63
32	0.09	0.22	0.43	0.72	1.09	2.13	3.58	5.46	7.81	10.65	13.99	17.87	27.27	39.00	53.16	69.86	89.21
34	0.09	0.23	0.45	0.76	1.16	2.27	3.80	5.80	8.30	11.31	14.87	18.98	28.98	41.43	56.48	74.23	94.78
36	0.10	0.25	0.48	0.81	1.23	2.40	4.03	6.14	8.79	11.98	15.74	20.10	30.68	43.87	59.80	78.59	100.36
38	0.10	0.26	0.51	0.85	1.30	2.53	4.25	6.49	9.27	12.64	16.61	21.21	32.38	46.31	63.12	82.96	105.93
40	0.11	0.27	0.53	0.90	1.37	2.66	4.47	6.83	9.76	13.31	17.49	22.33	34.09	48.75	66.45	87.33	111.51
42	0.11	0.29	0.56	0.94	1.44	2.80	4.70	7.17	10.25	13.97	18.36	23.45	35.79	51.18	69.77	91.69	117.08
44	0.12	0.30	0.59	0.99	1.50	2.93	4.92	7.51	10.74	14.64	19.24	24.56	37.50	53.62	73.09	96.06	122.66
46	0.12	0.31	0.61	1.03	1.57	3.06	5.14	7.85	11.23	15.30	20.11	25.68	39.20	56.06	76.41	100.43	128.23
48	0.13	0.33	0.64	1.07	1.64	3.20	5.37	8.19	11.71	15.97	20.99	26.80	40.91	58.49	79.74	104.79	133.81
50	0.13	0.34	0.67	1.12	1.71	3.33	5.59	8.53	12.20	16.63	21.86	27.91	42.61	60.93	83.06	109.16	139.39
52	0.14	0.36	0.69	1.16	1.78	3.46	5.81	8.88	12.69	17.30	22.74	29.03	44.32	63.37	86.38	113.53	144.96
54	0.14	0.37	0.72	1.21	1.85	3.60	6.04	9.22	13.18	17.96	23.61	30.15	46.02	65.81	89.70	117.89	150.54
56	0.15	0.38	0.75	1.25	1.91	3.73	6.26	9.56	13.67	18.63	24.48	31.26	47.72	68.24	93.03	122.26	156.11
58	0.15	0.40	0.77	1.30	1.98	3.86	6.48	9.90	14.16	19.30	25.36	32.38	49.43	70.68	96.35	126.62	161.69
60	0.16	0.41	0.80	1.34	2.05	4.00	6.71	10.24	14.64	19.96	26.23	33.50	51.13	73.12	99.67	130.99	167.26
62	0.17	0.42	0.83	1.39	2.12	4.13	6.93	10.58	15.13	20.63	27.11	34.61	52.84	75.56	102.99	135.36	172.84
64	0.17	0.44	0.85	1.43	2.19	4.26	7.16	10.92	15.62	21.29	27.98	35.73	54.54	77.99	106.32	139.72	178.41
68	0.18	0.47	0.91	1.52	2.32	4.53	7.60	11.61	16.60	22.62	29.73	37.96	57.95	82.87	112.96	148.46	189.56
70	0.19	0.48	0.93	1.57	2.39	4.66	7.83	11.95	17.08	23.29	30.61	39.08	59.66	85.30	116.28	152.82	195.14
72	0.19	0.49	0.96	1.61	2.46	4.80	8.05	12.29	17.57	23.95	31.48	40.20	61.36	87.74	119.60	157.19	200.71
74	0.20	0.51	0.99	1.66	2.53	4.93	8.27	12.63	18.06	24.62	32.35	41.31	63.07	90.18	122.93	161.56	206.29
76	0.20	0.52	1.01	1.70	2.60	5.06	8.50	12.97	18.55	25.28	33.23	42.43	64.77	92.62	126.25	165.92	211.87
78	0.21	0.53	1.04	1.75	2.67	5.20	8.72	13.31	19.04	25.95	34.10	43.55	66.47	95.05	129.57	170.29	217.44
80	0.21	0.55	1.07	1.79	2.73	5.33	8.94	13.65	19.52	26.61	34.98	44.66	68.18	97.49	132.89	174.65	223.02
82	0.22	0.56	1.09	1.84	2.80	5.46	9.17	14.00	20.01	27.28	35.85	45.78	69.88	99.93	136.22	179.02	228.59
84	0.22	0.57	1.12	1.88	2.87	5.60	9.39	14.34	20.50	27.95	36.73	46.90	71.59	102.37	139.54	183.39	234.17
86	0.23	0.59	1.15	1.93	2.94	5.73	9.62	14.68	20.99	28.61	37.60	48.01	73.29	104.80	142.86	187.75	239.74
88	0.24	0.60	1.17	1.97	3.01	5.86	9.84	15.02	21.48	29.28	38.48	49.13	75.00	107.24	146.18	192.12	245.32
90	0.24	0.62	1.20	2.02	3.08	6.00	10.06	15.36	21.96	29.94	39.35	50.25	76.70	109.68	149.51	196.49	250.89
92	0.25	0.63	1.23	2.06	3.14	6.13	10.29	15.70	22.45	30.61	40.22	51.36	78.41	112.11	152.83	200.85	256.47
94	0.25	0.64	1.25	2.10	3.21	6.26	10.51	16.04	22.94	31.27	41.10	52.48	80.11	114.55	156.15	205.22	262.04
96	0.26	0.66	1.28	2.15	3.28	6.40	10.73	16.38	23.43	31.94	41.97	53.60	81.81	116.99	159.47	209.58	267.62
98	0.26	0.67	1.31	2.19	3.35	6.53	10.96	16.73	23.92	32.60	42.85	54.71	83.52	119.43	162.79	213.95	273.19
100	0.27	0.68	1.33	2.24	3.42	6.66	11.18	17.07	24.41	33.27	43.72	55.83	85.22	121.86	166.12	218.32	278.77
110	0.29	0.75	1.47	2.46	3.76	7.33	12.30	18.77	26.85	36.59	48.09	61.41	93.75	134.05	182.73	240.15	306.65
120	0.32	0.82	1.60	2.69	4.10	7.99	13.42	20.48	29.29	39.92	52.47	66.99	102.27	146.24	199.34	261.98	334.52
130	0.35	0.89	1.73	2.91	4.44	8.66	14.53	22.19	31.73	43.25	56.84	72.58	110.79	158.42	215.95	283.81	362.40
140	0.37	0.96	1.87	3.13	4.79	9.33	15.65	23.89	34.17	46.58	61.21	78.16	119.31	170.61	232.56	305.64	390.28
150	0.40	1.03	2.00	3.36	5.13	9.99	16.77	25.60	36.61	49.90	65.58	83.74	127.83	182.80	249.18	327.48	418.16
160	0.43	1.10	2.13	3.58	5.47	10.66	17.89	27.31	39.05	53.23	69.96	89.33	136.36	194.98	265.79	349.31	446.03
170	0.45	1.16	2.27	3.81	5.81	11.33	19.01	29.01	41.49	56.56	74.33	94.91	144.88	207.17	282.40	371.14	473.91
180	0.48	1.23	2.40	4.03	6.15	11.99	20.13	30.72	43.93	59.88	78.70	100.49	153.40	219.35	299.01	392.97	501.79
200	0.53	1.37	2.67	4.48	6.84	13.32	22.36	34.13	48.81	66.54	87.44	111.66	170.45	243.73	332.23	436.64	557.54

Appendix 2. One thousand random numbers between 0 and 20 for general use in randomization procedures.

18	1	1	8	12	1	4	11	2	7	3	9	11	11	5	15	5	3	1	18	6	3	10	4	18
11	19	5	15	4	7	2	3	0	6	20	19	4	4	16	20	6	1	12	15	17	15	3	20	5
11	19	13	6	14	7	9	10	17	12	7	11	0	10	17	0	15	2	11	7	7	17	14	9	19
18	16	15	10	9	16	3	12	14	7	3	11	4	1	20	14	6	15	1	3	14	8	10	8	13
4	8	7	16	3	3	15	13	3	19	12	19	15	3	1	12	4	12	8	17	14	3	10	4	16
9	5	3	1	7	3	11	1	15	6	9	13	20	13	13	14	13	13	9	14	10	8	13	8	4
5	7	5	17	14	1	1	8	15	17	1	8	4	3	7	1	0	10	19	4	11	6	7	12	12
6	16	13	6	11	11	8	20	5	20	15	8	10	15	9	14	18	8	0	10	8	1	19	13	4
15	14	12	0	10	3	10	9	2	9	0	19	17	18	19	16	5	10	2	1	6	6	15	11	9
6	7	3	18	15	17	19	12	7	19	1	2	11	16	5	6	13	13	12	13	2	5	17	12	18
5	8	18	8	14	20	16	1	16	12	4	1	11	13	6	4	15	17	4	2	15	5	13	19	12
8	3	3	7	2	4	17	2	16	15	19	9	4	19	10	4	10	3	1	18	9	8	5	7	4
8	13	20	20	7	17	5	5	8	15	2	19	0	2	13	11	4	14	14	18	1	12	8	19	6
7	7	19	3	10	2	10	16	1	7	9	1	14	2	17	13	8	5	3	13	19	7	14	1	14
12	6	9	5	16	8	19	9	0	5	1	14	4	8	14	11	12	0	13	12	18	7	17	9	1
9	14	5	0	3	8	3	3	4	10	18	15	5	5	8	5	6	19	6	16	11	2	7	3	11
8	17	17	15	20	8	10	12	1	4	17	6	11	7	12	11	16	6	6	16	1	20	16	8	6
18	14	1	7	3	4	4	18	14	16	5	4	9	4	18	10	3	1	3	11	11	2	7	1	4
9	9	0	12	8	14	6	10	7	8	17	17	6	3	12	0	16	8	11	6	9	6	2	12	2
9	17	8	16	5	10	5	18	5	3	9	12	2	3	3	14	6	8	1	1	14	4	9	15	12
17	9	8	20	2	2	17	11	10	13	15	0	6	13	15	12	17	5	19	10	14	9	7	10	3
11	10	16	19	7	7	12	5	8	14	18	9	3	8	2	4	13	7	20	13	12	12	16	14	8
11	5	7	0	18	11	11	10	18	1	10	5	4	13	14	15	4	2	17	10	16	5	1	17	11
9	11	7	12	16	6	16	19	4	2	13	11	5	17	14	5	7	3	19	4	13	3	16	13	16
8	18	18	11	20	1	10	2	7	9	4	17	1	18	15	14	17	11	17	16	11	3	19	14	14
6	19	16	15	8	10	8	5	7	7	11	17	17	8	9	2	17	19	14	16	16	15	0	13	16
8	5	10	6	9	3	10	3	12	19	16	19	6	19	20	0	11	2	14	5	0	10	10	6	1
9	4	14	10	16	5	2	11	7	16	17	13	2	14	7	13	0	12	2	11	9	1	17	16	5
5	2	14	12	15	5	8	4	19	0	11	5	3	6	15	4	10	5	10	20	16	1	2	12	2
17	10	0	16	14	10	11	1	13	2	5	8	19	20	1	11	14	3	16	11	8	2	3	5	6
20	2	10	13	7	12	11	12	6	18	16	16	10	10	11	16	18	14	5	11	2	7	9	14	9
12	10	12	13	17	11	18	9	4	5	3	5	13	18	0	18	4	10	20	0	10	13	3	8	14
8	16	3	10	4	16	18	4	16	14	18	12	19	14	20	4	7	15	8	5	12	7	1	6	2
4	15	4	20	14	10	15	10	6	6	7	9	17	9	10	3	3	1	9	3	4	8	18	8	3
16	18	2	1	6	14	18	4	7	15	17	15	4	6	1	8	6	4	9	6	16	13	8	12	8
12	14	18	19	10	3	5	8	10	20	5	11	18	0	4	19	5	11	5	4	10	6	10	17	10
2	13	1	6	16	11	14	7	14	13	13	15	17	0	6	9	5	10	7	14	3	1	15	1	18
2	15	2	8	20	17	16	0	19	11	11	17	17	9	1	6	17	15	4	3	2	1	3	6	18
1	0	12	17	3	11	5	1	5	5	5	14	13	2	13	17	19	12	10	12	8	16	4	10	1
7	1	8	6	20	15	6	8	11	14	7	4	7	13	16	18	12	14	15	0	14	6	14	19	7

Appendix 3. Three hundred random numbers between 0 and 30 that are useful in positioning sampling quadrates within 900 m^2 plots.

20	8	26	14	19	2	28	22	22	28	3	5	7	29	10	2	2	25	5	14	4	11	16	14	1
14	24	10	19	28	12	0	9	14	28	16	20	5	17	26	9	15	11	30	15	17	19	13	29	22
13	27	15	12	13	15	23	1	3	17	21	4	12	14	23	28	3	23	7	14	5	25	5	23	25
19	27	26	9	24	16	29	12	17	2	10	8	17	15	4	4	27	28	27	16	28	2	6	13	7
17	22	19	7	15	20	22	5	22	14	19	15	25	22	11	29	30	10	25	7	24	22	28	3	16
21	5	1	14	19	4	3	23	28	15	10	7	11	5	9	17	16	3	15	25	20	23	5	1	30
11	15	23	21	14	25	28	1	17	30	2	25	9	26	3	11	8	25	13	7	27	8	14	7	26
5	18	19	5	16	26	16	19	10	16	22	17	6	30	15	19	25	7	23	8	7	22	14	8	23
3	3	10	15	27	4	16	2	1	5	2	4	8	19	25	23	12	1	2	9	4	19	22	3	14
8	10	22	1	7	28	9	13	21	4	12	9	17	7	12	18	24	23	17	25	8	29	8	5	21
13	24	20	11	26	19	5	17	27	21	13	26	27	3	24	22	27	19	24	19	20	16	12	27	18
2	5	8	4	3	4	1	30	17	2	30	28	6	6	12	27	9	23	7	22	14	20	21	17	12
13	24	13	18	15	12	21	3	30	18	29	5	14	12	18	8	24	5	9	22	26	22	17	20	15
5	6	28	1	17	20	13	16	13	14	9	3	10	4	10	26	21	8	13	26	26	27	5	24	13
29	9	24	2	22	20	13	19	24	21	6	4	15	12	3	28	0	28	22	24	23	26	25	2	20
8	25	20	7	27	13	16	14	9	7	18	6	18	28	12	13	3	21	6	29	19	30	19	6	4
14	9	30	7	5	11	20	8	16	8	8	19	21	25	20	14	21	15	12	1	8	24	16	19	20
11	18	22	23	27	21	19	17	1	24	26	21	27	12	19	9	22	27	18	7	4	27	3	28	28
10	2	3	29	14	8	17	25	8	6	7	12	17	23	29	3	0	26	17	19	15	11	3	8	22
1	10	0	9	12	7	23	23	20	23	28	7	6	20	2	19	8	27	6	21	11	23	11	12	4
18	16	20	1	28	23	10	3	1	11	2	3	7	15	27	21	2	27	27	24	12	10	18	1	22
26	0	24	15	0	13	17	29	3	9	22	1	29	19	14	13	3	12	13	24	25	22	8	23	28
29	29	8	26	22	3	28	22	6	10	10	5	3	8	8	2	11	28	8	12	10	29	22	18	15
2	28	29	5	28	18	26	25	16	19	12	14	2	23	22	28	10	19	17	11	4	10	20	14	9
20	3	15	23	25	23	14	17	18	28	12	23	14	10	9	9	30	27	5	24	9	0	10	28	27
4	28	23	29	16	16	6	11	9	27	17	27	22	3	18	25	3	10	2	9	20	11	6	15	28
14	1	11	25	22	9	12	6	18	2	12	7	8	27	8	18	15	22	1	13	2	18	14	9	21
11	5	3	8	26	0	23	27	11	5	0	20	28	1	15	20	4	22	2	3	27	30	1	6	12
4	7	27	5	25	17	4	10	13	12	1	27	15	1	17	8	3	21	18	2	4	10	26	13	2
27	20	27	8	22	25	18	14	13	4	6	15	11	24	20	30	5	12	28	11	4	28	20	18	10
4	21	18	15	3	18	24	19	17	29	25	27	14	19	25	5	16	15	19	14	30	1	11	11	17
7	18	19	20	13	1	29	25	30	18	24	18	21	4	13	25	17	13	29	20	16	29	2	11	12
1	24	16	23	12	11	25	0	14	5	29	21	9	10	3	21	21	21	2	7	22	20	1	23	25
1	4	25	23	15	6	8	3	13	10	28	14	1	6	28	18	10	28	7	21	18	4	13	8	26
26	18	20	27	6	17	13	10	16	1	0	12	26	28	28	10	9	7	29	23	15	20	24	2	21
14	22	11	2	25	2	9	15	10	15	5	2	11	23	9	24	14	8	5	16	14	26	12	24	1
20	24	23	3	19	27	7	25	7	18	16	2	3	8	27	10	28	14	23	25	27	12	22	22	28
10	27	21	1	22	29	29	8	17	20	16	21	28	5	22	15	23	29	20	2	29	2	25	29	12
28	12	20	21	30	1	11	6	20	24	3	18	11	29	22	30	18	16	2	28	2	24	2	24	6
12	2	25	28	26	22	9	14	3	23	13	16	22	18	24	11	1	24	2	26	27	18	19	27	11