Biomass estimates for forest in Guyana and their use in carbon offsets

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Executive Summary

A study was conducted to assess the carbon stocks of the rain forest in Guyana and their potential for carbon offset possibilities.
The report consists of two sections. The first sections deals with biomass and carbon stocks of various forest types in various regions in Guyana. In the second part a simple carbon model is being developed and with this model the effect of conventional and reduced impact logging is being compared.

Previous biomass estimates were not available for Guyana. Based on measurements of biomass of plots in neighbouring countries a first estimate for the living biomass of a typical Guyanan forest is 360 ton/ha. With total dead material and soil carbon included a first estimate for the carbon stock is 351 ton carbon /ha. Based on forest inventories and soil studies in central Guyana a more precise estimate could be made for several forest types. Whereas most areas in Guyana have total biomass (including litter) in the range of 250-300 ton/ha, some areas in central Guyana, on the Berbice formation, have markedly lower biomass (160-215). This could either be due to poor soil conditions or to historical fire occurrence in the central part of Guyana.

In central Guyana carbon estimates for different forest types were possible. The estimates, including soil carbon were:

Mixed forest on brown sand	224	t/ha
Mixed forest on loamy sand	260-358	t/ha
Mixed forest on laterite	286	t/ha
Mixed forest on lateritic clay	321	t/ha
Mora forest on alluvial clay	374	t/ha
Swamp forest on peat	400-650	t/ha
Wallaba forest on white sand	306	t/ha
Dry scrub in white sand	67-306	t/ha

With these estimates a total carbon stock for the Iwokrama forest comes up at 115 million tons of carbon for the 360,000 ha area.

Reduced impact logging has been shown to cause significant reductions in the carbon emissions of forestry operations in SE-Asia. Whereas timber output in Amazonian and Guyanan forest is lower than that of Asian forest, various studies have also shown that considerable reductions in damage are possible. Reduced impact logging often also leads to a higher efficiency of the logging operation.

A model, developed for this study, showed that while little information is available on the stocks and dynamics of soil organic matter in tropical forests, it is very important for a proper assessment of the effects of harvesting on the carbon fluxes. The model is sensitive to changes in SOM- turnover, the speed of forest recovery and product life-time. Because these parameters are insufficiently known the results are preliminary.

Logging in Guyana is either of low impact with an average of 10-20 m^3/ha (with relatively heavy damage) or high in some areas with local peaks of 70-100m^3/ha (with lower additional damage) and then non-existent in the adjacent areas.

In the first case the prospect of carbon offsets is not good. A reduction in logging damage will not lead to substantial changes in carbon emissions.

In the second case a reduction in damage will lead to changes in carbon emissions, amounting to 15 ton carbon/ha. However, a recent study showed that it is very difficult to reduce damage at such high extraction volumes. Even if damage could be reduced by 50% the total carbon gains for all of Guyana would be in the order of 20 million over a twenty year period.

It is concluded that the prospects for carbon offsets in Guyana are relatively small.

Further research should be directed at quantities and fluxes of large litter and soil organic matter and growth of forest after harvesting.

1. Introduction

Global Climate Change

Global climate change, arguably, is the most debated environmental issue ever. Over the last 130 years the mean annual global air temperature has risen about 0.6ºC (Gates 1993). 'Greenhouse gasses' such as carbon dioxide (CO_2, nitrous oxide (N_2O), methane (CH_4), ozone (O_3) and chlorofluorcarbons are held largely responsible for this increase. Greenhouse gasses have long lifetimes in the atmosphere - i.e. they will remain active for decades (or centuries as the case of chlorofluorcarbons). Evidence of the effect of greenhouse gasses is mounting and it now (almost) universally accepted that large scale emission of greenhouse gasses has given rise to rising temperatures.

The effects of global warming will be felt all over: sea level rise, heated interiors of continents, increased rainfall in wet areas, changing of ocean currents, glacial melt etc.

The best record of carbon dioxide changes have been made at the now world famous Mauna Loa site, Hawai. Since 1952 the atmospheric carbon dioxide concentration has risen from 315 ppm to 355 ppm in 1991 (Gates 1993). Burning of fossil fuel is largely responsible for this increase (at 5.5 Gt per year) but deforestation adds an approximate 2 Gt annually (Gates 1993, Tipper 1998). Oceans act as considerable sinks for atmospheric carbon (2Gt annually) and temperate terrestrial ecosystems likely act as considerable sinks as well. As the global climate warms, it is expected, however, that increased soil respiration will release part of this carbon, possibly creating a positive feedback (Gates 1993). More recently is has also been shown that tropical forests may act as moderate sinks for carbon (Grace *et al*. 1995a,b).

The most effective way of reducing carbon emissions is a drastic reduction of the use of fossil fuel. Solar, wind, wave generated energy and biomass fuel are potential zero-emission alternatives. This is at present an unlikely optimistic scenario.

Second best is planting of forest on deforested lands as a means of capturing carbon from the atmosphere. The effect of this measure must not be overestimated, as tropical grasslands are also considerable stores of soil carbon (Lugo *et al.* 1986, Lugo & Brown 1993, but see Nepstad *et al*. 1994) and the land areas required to capture sufficient carbon are substantial (Schroeder 1991).

Increasingly, forest conservation or low impact logging are seen as potential measures to mitigate greenhouse gas emissions. The use of such activities is based on two premises (Moura-Costa 1996):

1. Carbon dioxide, being a gas, circulates globally. Thus, efforts to offset emission will be equally effective anywhere on the globe.
2. Plants convert carbon dioxide into biomass through photosynthesis.

Moura-Costa (1996) defined a carbon-offset as "*the result of an action undertaken specifically to remove from and/or prevent the release of carbon dioxide into the atmosphere in order to balance emissions taking place elsewhere*". The "*specifically*" is important as a project has to have the intent to improve sequestration above a zero-action scenario. Thus, already established conservation areas are not likely to qualify, as no change is being achieved. Changing land-use plans from conversion to preservation does qualify and the difference in carbon stored between the two systems (forest - pasture) can be used as the offset. For land-use changes it is thus important to know the exact impact on carbon stores and fluxes of the alternate land-uses.

Four mechanisms may be available to utilise forestlands in carbon-offsets
1. Establishing plantations or reforestation on degraded or converted forestlands. The carbon-offset would be the difference between the carbon quantity in the final plantation or mature forest minus that of the present land-use.
2. Preservation of forestlands otherwise used for harvesting or conversion. The carbon-offset consists of the difference in carbon store of the untouched forest and the converted land.
3. Sustainable forest management for timber in selectively logged forest. The carbon offset is the reduction in carbon emissions over time due to lower harvesting damage. The latter can either be achieved by lowering felling intensity or by lowering the impact through improved felling techniques (RIL).
4. The use of biomass fuel as a substitute for fossil fuels, mainly firewood in the case of forest systems.

Each of these options requires a specific set of input parameters.

The aims of this study are to contribute to the development of possible mechanisms of carbon trade for Guyana, and are defined by its terms of reference to:
1. contribute to the likely mechanisms for the use of forest for carbon off-sets sales under the CDM of the FCC. This is largely to be provided by the issues paper already developed for UNDP.
2. give a description of the major forest types in Iwokrama and Guyana, highlighting their productivity, standing biomass and carbon storage/sequestration potential.
3. give a description of current logging practices for the major forest types in Guyana, highlighting their potential impact on both carbon emissions and uptake, summarising log outputs, fuel use and implications of vegetation disturbance from roading, smash, increased fire susceptibility.
4. provide insight in the potential for introducing carbon-saving, reduced impact logging techniques in Guyana.
5. determine future research needs, highlighting current conceptual problems and data availability problems in the specific context of Iwokrama, Guyana, the wider Guiana Shield area and tropical forests in general, specifically suggesting research that might be carried out at Iwokrama.

The report will first focus on the most reliable biomass estimates from countries close to Guyana and discuss which strategy will be used to estimate biomass for forest types in Guyana. First biomass estimates will be made for larger regions in Guyana than narrowing down to forest types in areas close to Iwokrama.
Then the report will discuss briefly the mechanisms of the carbon cycle and discuss the likely current effect of logging on the carbon balance and suggest ways of improvement. Finally some suggestions will be made for further research.

2. Biomass estimates of forests in the Neotropics

2.1 Total biomass estimates

Total biomass estimates are not available in Guyana but have been made in a number of neighbouring countries (Brazil: Klinge 1976, Russel 1983, Luizão 1995; Venezuela: Jordan 1989; French Guiana: Sarrailh 1990; Suriname: Poels 1987). These biomass studies will be discussed below to be able to put estimates of Guyana's forest biomass in some perspective.

2.1.1 Living biomass

The total living biomass of Amazonian/Guianan high forests ranges between 300-550 ton/ha (table 1).

The highest biomass is found in Suriname and Brazil on relatively good soils. Forests in Venezuela on very poor soils have roughly 25% less total biomass.

Above ground biomass

Total above ground biomass ranges from 250-450t/ha (Table 1, Saldarriga 1994). Small trees, due to their high abundance may account for a considerable portion of the total biomass. Lescure *et al*. (1983) attribute 10% of all biomass to trees under 20cm, 19% to trees between 0-40cm, and 71% for those over 40cm. In general all trees over 1 cm dbh constitute between 92-97% of all living biomass in the forest.

The partitioning of above ground biomass in high forest is rather constant over Amazonia: 68% for stems, 30% for branches, and 2% for leaves (Klinge *et al*. 1975 (Venezuela), Klinge 1976 (Brazil), Ohler 1980 (Suriname), Lescure *et al*. 1983 (French Guiana)). The forest in Kabo, Suriname, has extremely high biomass. Because this area is located on the white sands formation, this high figure is somewhat suspect (see also biomass equations below).

Forests on very poor or waterlogged soils generally have lower aboveground biomass (Table 2); Tall Caatinga, Venezuela, 277 t/ha (Klinge & Herrera 1983);Tall Bana, Venezuela, Brazil, 152-182 t/ha (Bongers *et al.* 1985, Luizão 1995); Low Bana, Venezuela, Brazil, 40-71 t/ha (Bongers et al 1985, Luizão 1995); Open Bana, Venezuela, 6 t/ha (Bongers et al 1985). These forests are somewhat comparable in stature to Wallaba forests, Dakama forests and Muri scrub in Guyana (Cooper 1979, Klinge & Medina 1979).

Below ground biomass

Root biomass is difficult to measure. Measured from small soil pits large roots are generally underrepresented and root biomass is underestimated (Russell 1983, Poels 1987). The best estimates are given by Russell (1983, Jari, Brazil, 103.5 t/ha), Klinge & Fittkau (1973, Manaus, Brazil, 130 t/ha - using a 50% conversion from wet to dry weight, Russell 1983), Poels (1987, Kabo, Suriname, 108.5 t/ha), each of which sampled the root zone to some extent. Values reported in literature range roughly from 60-130 ton/ha in the Amazonian/Guianan sites. Root-shoot ratio in high forest is in the range of 0.255-0.372 in Brazil (Russell 1983). Near San Carlos root-shoot ratios between 0.226 to 0.630 were reported (Russell 1983). Poels (1987) used 0.25 for Kabo.

Table 1. Biomass estimates for Amazonian and Guianan forests.

		Kabo (1) Suriname	Kabo (2)	ECEREX (3) French Guiana	San	Carlos (4) Venezuela	Jari (5) Brazil
Leaves	Trees > 5cm	6.5	7.6	4.41	8.0	8.6	8.5
	Trees < 5cm	1.5	1.5	0.98			0.2
	Palms	8.0	8.0	0.43	n.a.	n.a.	2.4
	lianas	0.5	0.5	0.10	1.0	1.0	
	total	16.5	17.6	5.9	9.0	9.6	11.1
Branches	trees > 5cm	84.9	94.0	93.24	49.9	52.3	
	trees < 5cm	29.8	23.6	0.65			
	palms				n.a.	n.a.	
	lianas	3.2	3.2	2.21			
	total	117.9	120.8	96.1	49.9	52.3	0.0
Stems	trees > 5cm	268.3	283.5	217.35	189.9	199.0	365.7
	trees < 5cm	1.0	1.0				
	palms	4.5	4.5	0.22			1.2
	lianas	6.6	6.6	5.16	14.7	14.7	
	total	280.4	295.6	222.7	204.6	213.7	366.9
Total above ground		414.8	434.0	324.8	263.5	275.6	378.0
roots	above ground				20.3	13.6	16.0
	below ground				35.4	35.4	103.5
	total	65.3	108.5		55.7	49.0	119.5
Total living		480.1	542.5		319.2	324.6	497.4
Litter	coarse	22.6	21.5		15.7	15.7	6.2
	decomposed		3.3		11.2	7.8	
	fine, in? soil	9.3	10.4				
	fine, above soil	2.9	2.9				5.7
	total	34.8	38.1		26.9	23.5	11.8
SOM	0-120 cm deep	129.2	172.7		46.5	47.6	
	120-170 cm deep		16.4				
	170-300 cm deep	27.0	27.0				
	total	156.2	216.1		46.5	47.6	
Overall total		671.1	796.7		319.2	324.6	

(1) Ohler 1980; (2) Poels 1987; (3) Lescure; (4) Jordan 1989; (5) Russell 1983.

Whereas root biomass decreases as aboveground biomass decreases its proportion increases in Venezuela (Jordan 1989, see also table 2). Root-shoot ratios in low biomass forests on poor soils is often above one. Similar root-shoot ratios are to be expected in Dakama forests and Muri scrubs in Guyana.

Table 2. Biomass estimates of forest on unfavourable soils.

Forest	Tall Caatinga (1)	Tall Bana (2)	Tall Heath Forest (3)	Short Heath Forest (3)	Low Bana (2)	Open Bana (2)
Guyana equivalent	Wallaba forest	Dakama forest	Dakama forest	Muri scrub	Muri scrub	Muri scrub
stems	163	118			21	1
branches	105	55			15	4
leaves	9	9			4	1
total aboveground	277	182	152	71	40	6
roots	135	128			69	42
leaf litter		4			3	2
wood litter		3			3	2
total small litter		7	7	5	6	4
root to shoot ratio	0.487	0.703			1.725	7.000

(1) Klinge & Herrera 1983; (2) Bongers et al 1985; (3) Luizão 1995.

2.1.2 Non-living biomass

Carbon is not only stored in living biomass. Dead biomass (leaf and woody litter), may amount to another 150-200 t/ha in high forest (Table 1). The standing stock of small litter (leaves, flowers, fruits, small twigs) is in the order of 6 to 10 t/ha.

Two forest types in central Guyana are at the lower end of the range - 4.5 for Wallaba forest and 5.6 for mixed Greenheart forest (Brouwer 1996). Litter layers in dry forests such as Dakama forest and Dakama-Muri scrub can be enormous (Table 3). Stark (1970) reported litter layers of close to 1 m thick in Dakama forest in Suriname and in similar Dakama forest in Guyana, Cooper (1982) measured a standing stock of 80 t/ha. These amounts are in striking contrast with the levels reported from forests of comparable structure on similar soils in Venezuela (Table 2). Coarse litter, including big fallen stems, is in the order of 15-25 t/ha (Table 1).

2.1.3 Soil organic matter

A large quantity of carbon is located in soil organic matter (SOM). This is the least known component of the total carbon stock of the forest (Nepstad *et al*. 1994). Poels estimates the SOM in Suriname at 150-200 t/ha. Jordan reports only 46-48 in San Carlos but Tiessen *et al*. (1994) report a maximum of 203 t/ha for organic C in forest on the to of a watershed near San Carlos, which would correspond with 350 t/ha of SOM. Their values for a mid slope site and bottom slope (waterlogged) site convert to a SOM quantity of 126 and 110 t/ha respectively. The three sites are very comparable to the Tall, low and open Bana of Bongers *et al*. in the same area (1983). Most studies measure SOM down to 100 cm at most. However, Nepstad *et al*. (1994) showed that huge carbon quantities can be present between 100 and 800 cm. At an average of 1000mg carbon per kg soil (0.1%), this may add up to 100 ton/ha! Similar quantities were reported for deep carbon by Trumbore *et al*. 1995, cited in Fearnside & Barbosa 1998).

Total SOM has never been quantified in Guyana. As a first indication we will rely on %organic carbon as encountered in soil analyses (Gross-Braun 1965, van Kekem *et al*. 1996) of the top soil layers (0-100 cm) and add deep soil carbon where deep rooting is expected. Brouwer (pers. comm.) estimates the carbon content of the soil (of mixed forest) in Guyana at some 156 t/ha, which includes 98t/ha for the deeper layers (sensu Nepstad *et al*. 1994).

2.2 Total organic dry matter

Based on the totals reported above (and 750 t/ha for forest near Manaus, Klinge *et al*. 1975) the range for total 'organic mass' in forest of Amazonia and the Guianas should be between 300-800 t/ha. Forest on poor soils are expected to be at the lower end of this range. Forest on more fertile soils, developed on the basement complex are expected to have somewhat higher biomass.

2.3 Biomass fluxes

2.3.1 forest turn over

Little information is available on forest turn-over in the Guianas. In French Guiana between 1.1 - 1.3% of the forest canopy is disturbed annually (van der Meer 1995). Neotropical rates usually fall between 1-2% (Hartshorn 1990). Forest turn-over rates are roughly equivalent to mortality rates of larger trees (0.5-3.6%, Phillips & Gentry1994).

2.3.2 litter fall

Litter fall in Neotropical rainforest is between 6-9 t/ha (Brouwer 1996). Wallaba forest in Guyana had an annual litter production of 7.7 t/ha, 4.5 of which was composed of leaf litter. Greenheart forest produced 9.1 t/ha, of which 5.6 leaves. Forest near St. Elie, French Guyana (poor soils) produced 7.8 t/ha annually (Puig & Delobelle 1988). In Suriname on more productive soils, annual litter production was 12.2 t/ha (ibid.).

Table 3. Annual small litter fall and litter standing stocks in selected Neotropical rain forests.

			Leaf fall t/ha/y	total small t/ha/y	leaf litter t/ha	total small t/ha
Guyana (1)	brown sands	mixed forest	5.4	9.1	2.5	7.4
Guyana (1)	white sands	wallaba forest	4.5	7.7	1.5	5.3
Guyana (2)	white sands	Xeromorphic woodland		7.8		7.5
Guyana (2)	white sands	Dakama forest		6.3		81.7
Guyana (2)	white sands	Dakama-muri scrub		5.4		65.9
Suriname (3)	white sands	Dakama forest				
French Guiana (4)		mixed forest	5.6	7.8		4.2
Brazil (5)	brown sands	mixed forest	5.5	7.8	2.8	6.5
Brazil (5)	white sands	tall caatinga	4.4	6.3	3.3	6.4
Brazil (6)		mixed forest	6.3	9.3	2.1	4.6
Brazil (7)		mixed forest	6.1	7.6	4.0	7.2
Trinidad (8)		Mora forest	6.9		4.1	

(1) Brouwer 1996, (2) Cooper 1982, (3) Stark 1970, (4) Puig & Delobelle 1988, (5) Luizao 1995, (6) Scott et al 1992, (7) Klinge 1973, (8) Cornforth 1970

2.3.3 decomposition

Because standing litter stocks in Guyana are smaller than the annual litter production, the residence time of small litter is less than a year, especially for leaves (Table 3). Decomposition rates of large litter (wood) are unknown. In general stumps disappear within 20 years. Greenheart is thought to have very slow decomposition rates but no data are available. For modelling purposes in tropical forests Nabuurs & Mohren (1993) used standard residence times of 10 year for dead wood, 1 year for small litter and 100 year for stable humus.

2.4 Conversion of biomass to carbon equivalents

Biomass is not equivalent to carbon. The carbon content of most biomass is around 50% (several of the above citations, Nabuurs & Mooren 1993) and this factor will be used to convert most biomass into carbon equivalents. Soil organic matter has a somewhat higher carbon content of 58% (Nabuurs & Mooren 1993). Using these conversion factors and San Carlos, Venezuela and St. Elie, French Guiana as the most comparable forest we now can make a first estimate of the total carbon content. With aboveground biomass at 300 t/ha, below ground at 60, total litter at 30, which together converts to 390 t/ha or 195 t C/ha and 156 soil carbon /ha our first estimate of carbon is 351 t/ha.

A first estimate of the total carbon of the rain forest in Central Guyana, based on measurements in neighbouring countries is 351 ton per hectare.

3. Estimates of biomass and carbon stocks in Guyana

As mentioned above biomass plots are not available in Guyana. Even if they were biomass is highly variable on a hectare basis thus a few plots would only give rough estimates. Total biomass is quite difficult (=time consuming) to measure. To obtain a reliable estimate based on total measurements would be prohibitively expensive, as it would include several plots in the major forest types.

Fortunately, allometric relationships between different portions of a tree are relatively constant and known for neighbouring areas. It is possible (with some uncertainty) to estimate height and biomass of a tree from its DBH (Brown *et al*. 1989, Brown 1998). Equations for such relationships have been developed for Brazil (Russell 1983), French Guiana (Lescure *et al*. 1983), Suriname (Jonkers 1987), and Venezuela (Jordan & Uhl 1978, Saldarriaga 1994). Brown *et al.* (1989) suggest to use such local equations, whenever available.

3.1 Biomass equations

In the simplest form the volume of a stem can be approximated by:

$$V = 0.7 * \pi D^2/4 * H$$

Where D is DBH and H is stem height. This is 70% of a cylinder with bottom surface equal to the basal area of the tree and length equal to stem height. This formula has been used in most large-scale inventories in Brazil, a.o. Radambrasil (Leite *et al.* 1974, Doi *et al*. 1975, Veloso *et al.* 1975). With wood density stem biomass can be calculated. Assuming constant proportions of biomass among stems, roots and leaves of the total tree biomass and assuming that trees constitute 97% (see above) of all biomass an estimate of total living biomass can be made. Table 1 shows that on average stem biomass is around 70%, which corresponds well with the conversion factors (BEF, Biomass Extension Factor) of 1.49 found by Brown *et al.* (1989, see also Brown 1998).

More elaborate equations have been developed. The best equations use DBH, H and wood density to estimate tree biomass. But as DBH is often the only measurement made in large-scale forest inventories this parameter is most often used. Equations based on field measurements are given in annex 1. Most equations have very high explaining power on a tree by tree basis but Lescure *et al*. (1983) found that their most accurate equation, on a tree by tree basis, gave the highest error when applied to whole stands (-22%).

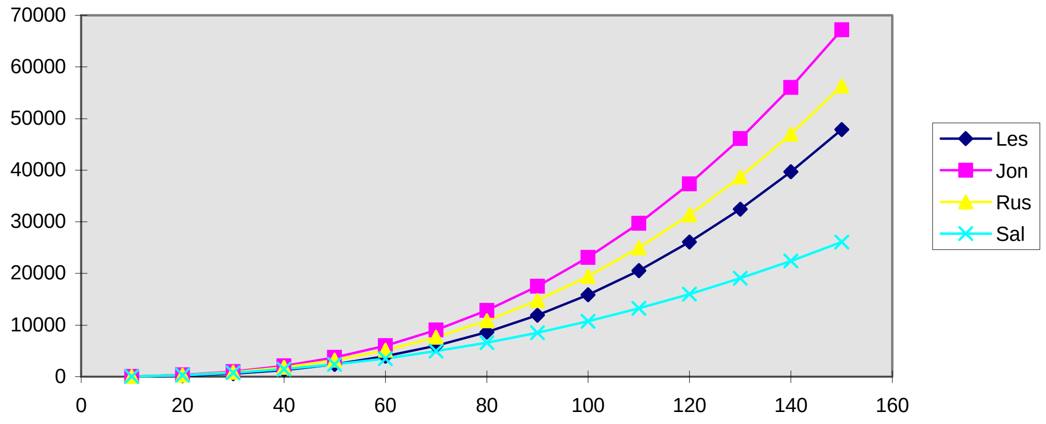

Figure 1. Total dry biomass of single trees as a function of DBH based on equations from French Guyana, Brazil, Suriname, and Venezuela.

Figure 1 shows the total aboveground biomass of trees as a function of DBH, as calculated on the basis of four equations for total tree aboveground biomass (Lescure *et al*. 1983, Russell 1983, Jonkers 1989, Saldarriaga 1994). There is considerable disagreement between the results of the various equations. As an example a tree with DBH of 100 cm is estimated at 15900 kg dry mass using the equations of Lescure *et al*. (1983) but with the equation from Suriname (Jonkers 1989) this tree is estimated to be 23100 kg dry mass. The differences cast considerable doubt as to the ‘universal’ usefulness of even ‘local’ biomass equations.

The biomass Jonkers (1989) calculated (383, 406, 324 t/ha. Table 5.4, page 94) agree with Ohler (1980) and Poels (1987), which were based on destructively sampled plots. Kabo is situated on the poor soils of the white sands formation and both Jonkers and Poels give their data as dry weight. The large difference is unclear to me but the total biomass estimates for Kabo would appear too high for the forests in central Guyana.

Because the forest in St. Elie is considerable closer in composition to that of Central Guyana than is the forest of Kabo, Suriname, **and** because the estimates of Lescure *et al*. (1983) agree very well with those of Brown *et al*. (1989) and Saldarriaga (1994), the equations of Lescure *et al*. (1983), which gave the least error when applied to whole stands, will be used to estimate biomass with forest inventory data in Guyana (see annex 1).

3.2 Methods to estimate carbon in Guyana’s forest

To estimate the carbon of Guyana’s forests forest inventory data will serve as our main source of data. Above ground biomass will be calculated on the basis of stand tables (first per forest region sensu ter Steege (1998), later per soil type for central Guyana only).

The procedure will be as follows:

Stand tables

For forest regions Guyana, stand tables will be developed from data of the Forest Industries Development Surveys (de Milde & de Groot 1970a-f, ter Steege 1998, Figure 2). Full information on tree dbh is available for 8 of 10 regions inventoried (ter

Steege 1998), the field data of which were made available by the Guyana Forestry Commission.

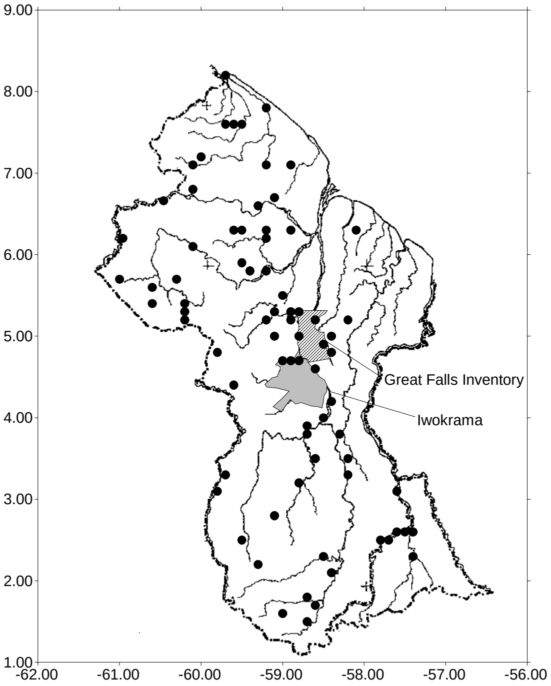

Figure 2. Location of FIDS plots, Great Falls Inventory area and Iwokrama Reserve Area.

For Central Guyana stand tables will be developed per combination of soil type and forest type (Fanshawe 1952, ter Steege *et al*. 1993). The main data are from the Great Falls Inventory (Welch & Bell 1970). Again field data (IBM punch cards) were made available by the Guyana Forestry Commission.

Both inventories only report on trees over 30 cm (12”). As considerable biomass is found in small trees, two lower size classes (10-20 and 20-30) will be constructed based on exponential decline of individuals between consecutive classes. This ‘decline’ will be determined with regression techniques and for each stand table separately.

Biomass

Aboveground tree biomass will be calculated with equations from French Guiana (Lescure *et al*. 1983), relating tree dry aboveground weight to DBH:

$$\text{Total Dw(kg)} = 0.05653D^{2.7248}$$

where D is diameter at breast height (cm). The equation is based on 914 trees with $r = 0.97$. (see also annex 1).

Below ground biomass will be estimated with a constant root-shoot ratio of 0.22 for mixed forest (Russell 1983, Jordan 1989, see above). For forests on white sand root-shoot ratios of comparable forest types in Venezuela will be used instead (Table 2).

Total living biomass will be estimated as a function of total tree biomass, assuming the proportion of tree biomass to be a constant 95% (see above).

Small litter will be estimated at 9 t/ha for mixed forests and 8 t/ha for Wallaba forest (for other forests on white sand data of comparable forest types in Venezuela and Brazil will be used instead, Table 2).

Large, woody litter is estimated to be 20 t/ha in undisturbed forest (Table 1).

Soil organic matter in the first 100 cm of the soil will be calculated from soil carbon content of soil layers (van Kekem *et al*. 1996; with additional data from Khan *et al*. 1980, Gross-Braun 1975). The amount in the layer from 100-700 cm will be calculated according to Nepstad *et al*. (1994) for forests in which deep rooting is expected.

Conversion of biomass to carbon

For conversion of biomass to carbon a constant 50% will be used, except in the case of soil organic matter where 58% will be used (Nabuurs & Mohren 1993).

3.3 Biomass in forest regions in Guyana

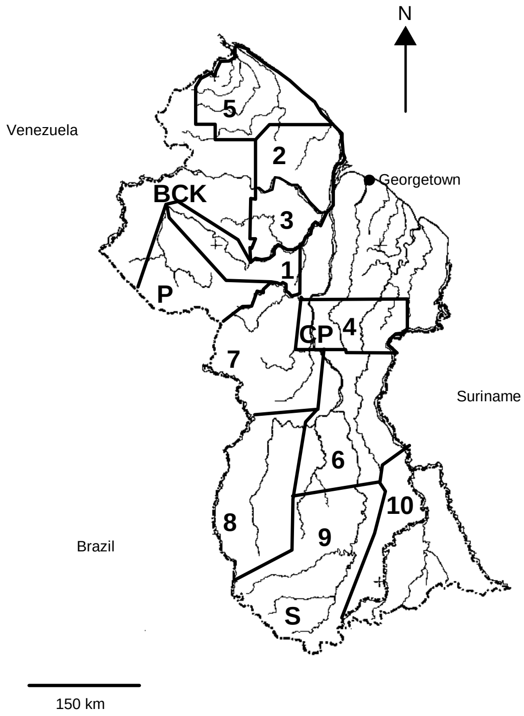

Figure 3. Forest Inventory areas in Guyana (based on de Milde & de Groot 1970 a&g).

Biomass for the forest regions in Guyana, as calculated with the stand tables of the FIDS give a tree above ground biomass between 121 and 203 t/ha.

Biomass, excluding litter, calculated with 70% of a cylinder, assuming a standard bole height of 18 m, and using specific wood density for each species, gives fairly comparable results. Very low biomass is encountered in zones 4 and 6, where the majority of the soils of the Berbice formation are found. Although the forests in central Guyana have a higher average timber density than those of south Guyana, the higher wood density cannot compensate for the low stocking.

Above ground biomass estimates for the major forest types in the 10 regions, based on basal areas, are given in annex 2. High biomass is found in mixed forests in zone 1, 2, 3, 4 west of the Essequibo river, 7 and 10. Low biomass is found in zone 4 east of the Essequibo, 6, 8 and 9 south of the Kassikaytu. In the area south of Bartica, Welch (1975) reports total wood volumes half of that of the neighbouring areas. Similarly low wood volumes are reported for north-eastern Guyana (Welch 1975). Biomass could not be accurately calculated for these area but will be approximately half of that of zone 1 (150 t/ha).

Table 4. Biomass estimates for forest in 7 inventory zones in Guyana.

	Trees	roots	other	large litter	small litter	total 1	total 2	total C
zone2	187	41	7	9	7	252	268	126
zone3	206	45	8	10	7	276	297	138
zone4	121	27	5	6	7	166	182	83
zone6	140	31	5	7	7	190	215	95
zone7	203	45	8	10	7	272	275	136
zone9	171	38	6	9	7	232	257	116
zone10	218	48	8	11	7	293	294	146

The first six columns are calculated as described in the text. Total 2 is based on wood density and individual species volumes (see text. For zone 1 and 5 no dbh is available, zone 8 is mainly savannah).

3.4 *Biomass and carbon stocks in forests in central Guyana*

In the following first an overview of the data is given in table form. After that the most common soil-forest combinations in central Guyana will be discussed.

stand tables

Stand tables for the forests in central Guyana are given in Table 5 This area is adjacent to the northern boundary of the Iwokrama area and sufficiently similar for comparative purposes.

Table 5. Stand table (trees/ha) of forests on stratified by soil type.

Mid class (cm)	14	24	34	44	55	65	75	85	95	105	116	126	136	146
brown sand	107.0	61.0	34.8	26.2	14.3	8.4	3.7	1.5	0.7	0.4	0.2	0.1	0.0	0.0
clay	102.8	56.4	31.0	23.1	12.1	6.8	2.8	1.5	1.1	0.5	0.1	0.0	0.1	0.0
laterite	69.3	41.9	25.3	23.4	13.5	6.4	3.4	1.4	0.8	0.5	0.2	0.0	0.1	0.1
loam	111.6	64.5	37.2	27.4	16.2	9.6	4.1	1.7	1.1	0.4	0.4	0.1	0.1	0.1
pegasse	170.0	87.9	45.4	25.0	10.5	6.7	3.2	1.7	0.2	0.2	0.0	0.2	0.0	0.0
white sand	186.1	94.5	48.0	28.7	14.7	7.0	3.2	0.2	0.4	0.0	0.1	0.0	0.0	0.0

Classes 34-146 derived from raw data of the Great Falls Inventory. Classes 14 and 24 estimated with exponential regression.

biomass estimates

Biomass estimates based on the stand tables of Table four are given in table 6. Most estimates fall well within the range of Brown *et al*. (1983) for wet forest. Only forest on lateritic soil has somewhat lower biomass, due to low number of trees per area.

Table 6. Biomass estimates (t/ha) and plant carbon of forests stratified by soil type.

	trees	roots	other	large litter	small litter	total biomass	total carbon
brown sand	256	56	10	13	7	342	171
clay	229	50	9	11	7	307	154
laterite	223	49	8	11	7	299	150
loam	293	64	11	15	7	391	195
pegasse	246	54	9	12	5	326	163
white sand	248	55	9	12	5	330	165

Biomass of trees estimated from raw data of the Great Falls Inventory (table 5).

soil carbon estimates

In Table 7 percentages of soil organic matter are given for the major soil types in Central Guyana (van Kekem *et al*. 1996). Deep rooting is expected in forest where dry season water shortages are likely to occur in the upper soil layers (see Nepsatd *et al*. 1994) but not in soil with high water tables or impermeable layers (such as rock). Pegasse soils (Histosols) have been largely neglected in soil surveys, as this soils type covers only a small fraction of the land area in central Guyana (<2%). However, due to their large accumulation of organic material in the soil they may be of great importance for the carbon store of forest areas. Organic material for these soils is based on information from the coastal area (Gross-Braun 1975), which represent the only current available information.

Table 7. Percentages organic carbon (OC) and carbon storage for soil types in Central Guyana

Depth	bulk density[1]	brown sand	clay	laterite	loam	pegasse[1]	White sand
0-20	1	2.4	3.5	2.5	0.9	27.2	1.4
20 - 50	1.3	0.6	1.4	1.3	0.5	33.1	0.2
50 - 100	1.4	0.3	0.6	0.5	0.3	9.9	0.1
100-800	1.4	0.1	?	?	0.1	?	0.1
SOM t/ha							
0-100		65	167	136	65	490	43
100-800		98	?	?	98	?	98

Based on van Kekem *et al*. (1996). Pegasse soil data based on Gross-Braun (1975).

[1] Bulk density of all soils equal but for pegasse soil of first two layers estimated at 0.9, that of the third layer at 1.

3.4.1 Mixed forest on brown sands

In Guyana, forests on the brown and loamy sands of the Berbice formation are almost invariably characterised by the presence of species of the genera *Eschweilera* and *Licania*. Characteristic species, which may become locally dominant are *Eschweilera sagotiana, E. decolorans, E. confertiflora, Licania alba, L. majuscula, L. laxiflora, Chlorocardium rodiei, Mora gonggrijpii, Alexa imperatricis, Vouacapoua macropetala, Swartzia schomburgkii, S. leiocalycina, Catostemma commune, Eperua falcata, Pouteria guianensis, P. cladantha, Aspidosperma excelsum,* and *Pentaclethra macroloba* (Fanshawe 1952). Several sub-divisions are possible but ‘forest associations’ sensu Fanshawe can be very localised and small in area and, even at watershed level (<500 ha), impossible to map (ter Steege 1993, ter Steege et al. 1993).

In the forests on brown sands of the Great Falls Inventory area the ten most common species are *Mora gonggrijpii, Chlorocardium rodiei, Eperua falcata, Eschweilera sagotiana*, *Dicymbe altsonii, Swartzia leiocalycina, Eschweilera grata, Catostemma* sp., *Licania* spp., and *Pentaclethra macroloba*. The forest is approximately 35m high (21-51m, Welch & Bell 1971).

Mixed forests on brown sands have an average number of trees per area (Table 5). The total biomass estimate for this forest is 342 t/ha (Table 6) giving a carbon estimate of 171 t/ha.

There is an average amount of organic carbon in the soil of brown sand forest (Table 7) and deep rooting is expected because of the sandy structure of most brown sands. Thus carbon for the soil between 100 and 800 cm is estimated according to

Nepstad *et al*. (1994) at 98 t/ha (Table 5). This brings the total at organic carbon on the soil at 163 t/ha and that of the forest at 334.

The total carbon of mixed forests on brown sands is estimated at 334 t/ha

3.4.2 Mixed forest on loamy soils

The ten most common species in mixed forest on loamy sands are *Dicymbe altsonii, Chlorocardium rodiei, Swartzia leiocalycina, Mora gonggrijpii, Eperua falcata, Eschweilera sagotiana, Eschweilera grata, Clathrotropis brachypetala, Carapa* spp*.,* and *Pentaclethra macroloba*.

Mixed forests on loamy sands have an average number of trees per area (Table 5) but relatively more large ones. The total biomass estimate for this forest is thus the highest of all forest types, 391 t/ha (Table 6) giving a carbon estimate of 195 t/ha.

There is an average amount of organic carbon in the soil of brown sand forest (Table 7) but deep rooting is not necessarily expected. Consequently organic carbon on the soil at may range between 65-163 t/ha and that of the forest between 260-358 t/ha.

The total carbon of mixed forests on loamy sands may range between 260-358 t/ha

3.4.3 Mixed forest on lateritic soils

The ten most common species in mixed forest on loamy sands are *Swartzia leiocalycina, Eschweilera sagotiana, Vouacapoua macropetala, Eperua falcata, Pentaclethra macroloba, Clathrotropis brachypetala, Mora gonggrijpii, Chlorocardium rodiei, Eschweilera grata, Carapa* spp.

Mixed forests on lateritic soils have a low number of trees per area (Table 5) but relatively more large ones. The total biomass estimate for this forest is 299 t/ha (Table 6) giving a carbon estimate of 150 t/ha.

There is a high amount of organic carbon in the top soil of forest on laterite (Table 7) but deep rooting is not expected because of the hard structure of the soil material. Organic carbon in the soil at is probably equal to that of the top soil at 136 t/ha and that of the forest 286 t/ha.

The total carbon of mixed forests on lateritic soils is probably around 286 t/ha

3.4.4 Forest on clay soils

In the Great Falls inventory the ten most common species on clay soils are *Mora gonggrijpii, Eperua falcata, Chlorocardium rodiei, Eschweilera sagotiana, Mora excelsa, Swartzia leiocalycina, Carapa* spp*. Pentaclethra macroloba, Licania* spp., and *Clathrotropis brachypetala*. Thus forests on clay soils are a mixture of forest on the clayey phase of lateritic soils with *Mora gonggrijpii, Eperua falcata, Chlorocardium rodiei, Eschweilera sagotiana,* and *Swartzia leiocalycina* and Mora forests along creeks and rivers, dominated by *Mora excelsa, Eperua rubiginosa, Carapa* and *Pentaclethra*.

The forests on clay soils have a low number of trees per area (Table 5) but relatively more large ones, which is identical to the situation on laterite. The total biomass estimate for these forests is 307 t/ha (Table 6) giving a carbon estimate of 154 t/ha. This is very close to the figure of forest on lateritic soils.

An estimate of biomass based on a Mora forest plot in Iwokrama (data from Johnston & Gillman 1995) amounts to a biomass of 414 t/ha, due tot the high occurrence of large *Mora excelsa* trees. This converts to a carbon stock of 207 t/ha.

For forest on lateritic clay similar soil organic matter is assumed as for those on other laterite (134 t/ha). Thus the total carbon stock is estimated at 321 t/ha.

Alluvial clay has 167 t/ha of carbon. Because of the high water table deep root are unlikely and this is estimated to be the total carbon stock. Mora forest on alluvial clay is expected to have a carbon stock of 374 t/ha.

The total carbon of mixed forests on lateritic clay soils
is probably around 321 t/ha

The total carbon of Mora forests on alluvial clay soils
is around 374 t/ha

3.4.5 Swamp forest on pegasse soils

The ten most common tree species in swamp forest on pegasse (peat) soils are *Carapa* spp*., Eperua falcata, Dicymbe altsonii, Tabebuia insignis, Catostemma* sp*., Mora excelsa, Eperua grandiflora, Cassia cowanii, Ormosia coutinhoi, Iryanthera* sp.

The white sands area has a gently rolling aspect with a drainage pattern of many small creeks. The water table in the heads of such creeks is perpetually high and often in such gullies swamp forest is found on a layer of peat soil (pegasse). Dominant species area *Jessenia bataua, Mauritia flexuosa, Tabebuia insignis, Clusia* spp., *Symphonia, Iryanthera, Couratari, Eperua falcata, Diospyros*. The forest is very open and a dense layer of herbs is found. This layer is often dominated by *Rapatea paludosa* (ter Steege *et al*. 1993). In the lower reaches of creeks a variety of soils is found ranging from redistributed sands to clays. Common tree species in these creek forests are *Mora excelsa, Eperua rubiginosa, E. falcata, Pterocarpus officinalis, Carapa* spp*., Inga* spp. and *Pentaclethra macroloba*.

Swamp forest is characterised by a high occurrence of small stems. Big trees are rare. Biomass of swamp forest is 326 t/ha (Table 6), which converts to 163 t C/ha.

Because of the high water table decomposition is low and peat is formed. Depending on the thickness of the peat layer huge quantities of carbon can be stored. An estimate for a peat soil (50 cm thick) in a creek in the coastal area was 1979 t C/ha. This is ten times the quantity of other soils. Given an organic matter percentage of 50% (50% of which Carbon) each ten cm of peat is roughly equivalent to 245 t C/ha (Table 7). There are no data for peat soils in the interior, because the areas are considered too small to map (Gross-Braun 1975) or too small to be important (van Kekem *et al*. 1996).

Assuming that 10 cm of peat is a minimum for a swamp soil to be classified as peasse, and that the layer of peat can be as deep as 100cm in the coastal swamps, the organic carbon store of swamp forest is anywhere between 400 to 2600 t/ha. Van Kekem *et al*. (1996) estimate the peat layer in central Guyanan swamp forest between 10-20 cm.

The total carbon of Swamp forests on pegasse soils in central Guyana may be between 400-650 t/ha

3.4.6 High forest on white sand (Wallaba forest)

High forest on white sand (dry evergreen forest, high, well developed heath forest) locally called Wallaba forest occurs on the excessively drained White Sands (albic Arenosols). Dominant species are Soft wallaba (*Eperua falcata*) and Ituri wallaba (*E. grandiflora*). Other common species are Awasokule (*Tovomita* sp.), Itikiboroballi (*Swartzia* sp.), Yareola (*Aspidosperma excelsum*) and Baromalli (*Catostemma* cf. *fragrans*). Korokororo (*Ormosia coutinhoi*) is found near the borders with lower, swampy areas (ter Steege *et al*. 1993). The 10 most common species in the Great Falls Inventory were: *Eperua falcata, Eperua grandiflora, Dicymbe altsonii, Catostemma sp., Ormosia coutinhoi, Talisia squarrosa, Licania spp., Aldina insignis, Chamaecrista adiantifolia, and Chlorocardium rodiei.*

Forest on white sands is characterised by a small amount of trees of large diameters but a very high number of small trees (Table 5). The total biomass estimate for this forest is 330 t/ha (Table 6) giving a carbon estimate of 165t/ha.

There is little organic carbon in the soil of white sand forest (Table 7) but deep rooting is very much expected (and observed in Suriname, T. Pons pers comm.), thus carbon for the soil between 100 and 800 cm is estimated according to Nepstad *et al*. (1994) at 98 t/ha (Table 5). This brings the total carbon in the soil at 141 t/ha and the total for the forests at 306 t/ha

The total carbon content of high white sand forests is estimated at 306 t/ha

3.4.7 Low forests on white sand soils

Dakama forest

There were no stand tables available for Dakama forest in central Guyana. Whitton (1962) provides some data of similar low forests on white sands in the Pakaraimas. Based of the stand table a biomass of 230-330 t/ha can be estimated with a carbon content of 115-165 t/ha. This is comparable to the tall Bana in Venezuela (Bongers *et al* 1985, see table 2 above). Because the biomass of Dakama forest will depend on the time of recovery after the last fire the biomass without litter will vary between 90 (low Bana like) - 250 t/ha and approaches that of Wallaba forest if left alone long enough. The litter layer may be enormous but again variable. In poorly developed Dakama scrub no more than 10 t/ha should be expected but in well developed Dakama forest it may be as high as 80 t/ha (Cooper 1982). Because Dakama forest is undoubtedly water stressed where it occurs on the top of watersheds deep rooting must be expected.

Using carbon estimates for white sand soil the carbon stock of a poorly developed Dakama forest can be as low as 206 t/ha (60 biomass, 5 litter, 43 upper soil, 98 deep soil) and as high as 346 t/ha (165 biomass, 40 litter, 43 upper soil, 98 deep soil). Where Dakama forest/scrub occurs on gleyic podzols (Ituni sands), deep rooting is not expected and the carbon stocks may be 100 t/ha lower or 76 t/ha for the most degraded form.

Muri scrub

Muri scrub is very open with large areas of open soil between islands of low vegetation. Similar scrub in Venezuela had an aboveground biomass (including litter) of only 6 t/ha but with a root biomass of 42 t/ha (Table 2). Deep rooting is to be expected on the excessively drained locations but is likely to be in proportion of the root biomass of the upper layers (1/3 of that of well developed white sand forest). A rough estimate of carbon for Muri scrub would thus be in the order of 99 t/ha (24 biomass, 43 upper soil, 32 deep soil). On the groundwater podzols deep rooting may be absent and carbon stocks could be as low as 67 t/ha

There is insufficient information on biomass of degraded white sand forests. The carbon stocks will depend on location (excessively dry or waterlogged) and degree of disturbance. Estimated stocks range between 67 and 306 t/ha.

3.4.8 white sand savannahs

Complete degradation (continuous burning) of forest on white sands may lead to white sand savannahs, such as found close to Soesdyke. There is no information available on biomass and carbon stocks of this vegetation. Deep rooting under pasture is less than under forest and deep carbon will slowly decrease after conversion (Nepstad *et al.* 1994).

3.4.9 brown sand savannahs

Pastures have been developed on the browns sands of the ‘intermediate savannah’. Most of the converted lands were already savannah. No biomass estimates are available. Carbon content of the savannah soils is not unlike that of forest (see Fletcher 1989)

3.5 Forest types in Iwokrama and their carbon stocks

The Iwokrama reserve area of 360,000 ha is situated in central Guyana, just below the Great Falls Inventory Area. Although some remarkable differences exist both in floristic composition (pers. obs.) and mammal occurrences (G. Watkins pers. comm.). The main species composition of Iwokrama’s forests will not differ to such an extent as to change to carbon content significantly (except for the higher altitude forest on the Iwokrama mountains possibly). Table 8 lists the forest types of Iwokrama (courtesy V. Datadin) and their potential carbon stock.

The total area is slightly larger than 360,000 ha. The total estimated carbon stock is estimated to be 116 Mt. Further information on above ground biomass can be found in Table 6 and Annex 2 (Iwokrama is situated mainly in zone 7, with small parts in zone 6 and 4). Because biomass is lower in forest surrounding the Rupununi savannah (see zone 6, 8 and 9) it is expected that the biomass will decrease towards the southern boundary.

Table 8. Forest types of Iwokrama and their approximate carbon stocks[1].

forest type	area ha	Carbon t/ha	total carbon Mt/ha
Mixed forests			
or flat or gently undulating terrain	170120	334	56.8
on flat terrain along main rivers	4997	334	1.7
Liane forest	1736	250	0.4
small crowned on flat to undulating sandy terrain	42479	250	10.6
on steep high hills	89132	286	25.5
Wallaba Forests			
on flat white sand ridges	7085	306	2.2
poor Wallaba-Dakama forest on flat white sand ridges	3503	200	0.7
low open Dakama-Muri scrub on flat white sand ridges	7431	67	0.5
Swamp Forest			
low swamp forest	2975	400	1.2
Mora forest	13324	374	5.0
marsh swamp forest	11665	374	4.4
mixed forest/swamp forest	274	334	0.1
swamp forest/wallaba forest	16582	400	6.6
clearings	42		
Total	371345		115.7

[1] Figures in italics have been (gu)estimated on the basis of physiognomy and carbon of other forest types.

4. Carbon emissions in conventional and reduced impact logging

Low impact logging can be used as a carbon offset method. Tropical forest are considered to provide better opportunities than do temperate forests (Nabuurs & Mohren 1993, see also Moura Costa 1996). The method has been used successfully in the tropical forests of SE-Asia (e.g. Putz & Pinard 1993, Moura Costa 1996, Dijkstra 1998, see belwo).

Apart from income generation as a result of carbon offsets, RIL can also result in considerable financial savings because of a higher efficiency with which heavy logging equipment is used (eg. Hendrison 1990, see below).

Several studies have shown that damage control in logging operations can lead to considerably less damage to the remaining stand (Australia: Crome *et al*. 1992; Sabah: Cedergren *et al*. 1994, Pinard & Putz 1993, 1996, Marsh *et al*. 1996; Kalimantan: Sist & Bertault 1998, Sist *et al*. 1998, Karsenti 1998; Brazil: Blate 1997, Johns *et al*. 1997, Sarre *et al*. 1996, Winkler 1997). In Suriname the CELOS Management system was developed (de Graaf 1986, Poels 1987, Jonkers 1987, Hendrison 1990). Adoption and modification of this system was on of the projects of the Tropenbos-Guyana Programme (van der Hout 1997, van der Hout & van Leersum in press).

Important elements of Low Impact Logging (LIL) or Reduced Impact Logging (RIL) as compared to Conventional Logging (CNV) are:

1. More comprehensive planning of activities
2. climber cutting 1 year prior to harvest
3. directional felling to avoid damage to potential crop trees and to facilitate skidding.
4. Winching

Substantial savings in terms of carbon can result from reducing damage to the remaining stand (see references for Sabah, Kalimantan above).
In the following we will look at a few examples of RIL studies in SE-Asia, Brazil, Suriname and Guyana. From these studies we will develop a list of activities that may help to improve the carbon balance of a forestry operation.

4.1 Some examples of ‘reduced impact logging’ studies

Southeast-Asia

Logging intensities in SE-Asia are high. Pinard and Putz (1996) report a range 8-15 trees per ha representing 50-120m^3 timber. Similar amounts are reported by (Marsh *et al*. 1996). During harvest 40-70% of the remaining stand is damaged (Putz & Pinard 1993, Marsh *et al*. 1996). By implementing RIL skid trial amount to only 67 m/ha compared to 199 m/ha with CNV. Whereas CNV typically destroys 41% of all trees this is only 15% with RIL (Marsh *et al*. 1996). The damage for CNV amounts to a carbon loss over time of 95 t/ha. Reduced Impact Logging (RIL), by reducing the damage to the remaining stand, may result in a saving of an estimated 43 t carbon/ha at a cost of $3.75/t after two years (Putz & Pinard 1993, Pinard & Putz 1996). This is cheaper by a factor of two compared to carbon sequestered through plantation forest. The ‘low cost’ of carbon sequestration through RIL has resulted in investments from US power companies in RIL projects in SE-Asia (Pinard & Putz 1993, Dijkstra 1998).

Whereas reduction in skidding results in substantial reduction of damage, this is not necessarily the case in felling (Sist & Bertault 1998, Sist *et al.* 1998). Directional felling can be used to avoid damage to Potential Crop Trees (PCT) but as trees are everywhere in the forest felling a tree without damage to the rest of the stand is impossible (see also van der Hout & van Leersum in press).
A major cost saving in RIL is the skidding efficiency (a.o. Hendrison 1990, Karsenti 1998). However in plot studies the variability between plots is too high to evaluate all aspects properly (Karsenti 1998) and large scale experiments are necessary to test this. Net benefits are in the order of US$ 50-74/ha, which is considered 3-4% in the margin in Sabah and which could hamper implementation there (Karsenti 1998).

Brazil
Studies in Brazil also show that RIL is feasible (see citations above) and larger scale projects (Demonstration Forests), based on these studies, have been carried out by the Tropical Forest Foundation (Blate 1997). The benefits of RIL in Brazil can be summarised as follows (Uhl *et al*. 1997, Blate 1997):

1. reduction of logs left un-retrieved in the forest (7m^3/ha!)
2. reduction of waste due to better felling techniques (0.75 m^3/ha)
3. less damage (30% fewer trees) to remaining stand
4. less damage to canopy (25%)
5. increased productivity, especially that of heavy machinery (by 20%)
6. reduction of cutting cycle

One study (Johns *et al*. 1996) showed that on an area basis RIL affected 1503 m^2/ha compared to 2276 m^2/ha in CNV. The largest differences were found in:

1. manoeuvring skidders (or dozers) in the stump zone: 23-45 m^2/ha (RIL) vs. 254 m^2/ha (CNV)
2. log landings 61 m^2/ha (RIL) vs. 203m^2/ha (CNV)
3. Roads were also wider in the CNV operation compared to RIL and caused a disturbance of 336 m^2/ha compared to 203 m^2/ha in RIL

At least one company is attempting to use RIL techniques commercially (Precious Woods, Mill Madeira). The results of a case study at this site clearly show that RIL is feasible under commercial conditions (Winkler 1997) and may result in substantial reductions in damage to the forest:
1. less damage to PCTs (22.2% vs. 51.5%)
2. less forest area affected (4.5% vs. 20%)
3. less canopy disturbance (10.8% vs. 24.7%)
4. less timber losses (3.9% vs. 8.5%)

The cost of RIL compared to CNV in this study were considered not higher (1.5%) and it was concluded that RIL is not necessarily more expensive than CNV but has great advantages in other economic, social, and environmental objectives (Winkler 1997).

Suriname

Less damage and higher returns are also features of the CELOS Management System (CMS), which consists of the CELOS Harvesting System (CHS) and Silvicultural System (CSS). Aspects of the CMS are described in a number of publications (a.o. de Graaf 1986, Poels 1987, Jonkers 1987, Hendrison 1990). In applying the CHS the damaged forest area could be reduced by half, while at the same time skidding cost decreased by some 20% (table 9). Sufficient regrowth of commercial stock can only be achieved by killing non-commercial trees in a number of treatments after felling (de Graaf 1986). Whereas the CHS was tested at a semi-practical scale the CSS has never been tested at such scale.

Table 9. Logging costs (US\$/m^3) of the CELOS system compared to CNV.

	CELOS	CNV
Labour	6.20	3.60
Felling	1.85	1.00
Presorting	4.20	n.a.
Skidding	8.00	19.50
Total	20.25	24.10[1]

Source Hendrison (1990), prices from 1988. [1] this total compares very well to the estimated cost of harvesting up to the log market in central Guyana of US$ 22 (Flaming 1995)

Guyana

The forest in central Guyana has characteristics that set it apart from most other tropical forests - its is often dominated by one or a few species (Fanshawe 1952). Often such dominant species are commercial as in the case of Greenheart (*Chlorocardium rodiei*), Mora (*Mora excelsa*), Morabukea (*M. gonggrijpii*), Wallaba (*Eperua falcata, E. grandiflora*). Other parts of the forest may have very little commercial stocking[1]. The clumped occurrence of Greenheart, until recently, Guyana's main exploited timber leads to over-utilisation of certain forest areas and under-utilisation of others. As an example, whereas the average extraction of a company in central Guyana may be as low as 3-5 m^3/ha, more localised extraction levels may reach up to 70-100m^3/ha (Clarke 1956, ter Steege *et al* 1996, Zagt 1997). Forest that has been exploited at such level shows, obviously, very little prospect for harvests in the near future with initial commercial regrowth of Greenheart of only 0.01 m^3/ha (ter Steege 1990).

It is difficult to define conventional logging. CNV may span the gamut from complete destructive behaviour to fairly environmentally sound harvesting techniques (van de Hout & van Leersum in press). Thus it may be difficult to define an average standard for the current Guyanese logging but profitability of most companies appears to be low (Landell-Mills 1997).

The studies above have clearly shown that a substantial reduction in damage can be achieved through RIL. However, local conditions (log sizes, volumes harvested) determine to a great extent the logistical possibilities (van der Hout and van Leersum in press).

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[1] In part this may be caused by the fairly narrow choice of commercials in Guyana, often less than 20 species.

4.2 Where can reduced impact logging improve the carbon budget?

RIL may result in considerable improvements from a forest management point of view. Several of these improvement will also have an effect on the carbon balance of the forest as was shown in the case studies in SE-Asia (see above).
Listed below are specific actions in RIL that affect the carbon balance:

1. reducing road width and length
2. reducing felling damage
3. reducing losses
4. reducing skidding damage
5. utilising waste more efficiently

In the following an attempt will be made to quantify these ‘improvements’ in a carbon context. Under each heading we will discuss the savings from a RIL case studies point of view and review information as available for CNV logging in Guyana

1. reducing road width and length

Case studies

In Brazil, reductions in log landings and road area were from 4.6% to 2.7% per ha (Johns *et al.* 1996). Assuming most biomass will be decomposed this adds up to (1.9% of 335t/ha) just over 6 t/ha, equivalent to 3 t Carbon/ha. Half of which will be released over a 20 year period, the other half over a longer period. The reduction in fossil fuel consumption is negligible[2]. Because fuel and machine time are both costly items reducing the use of buldozers will be essential for cost cutting. The difference at the F2M site (Winkler 1998) is far less, because the same forest road system is being used. Log landings were also smaller here (0.40% vs. 0.63%) being just over 0.6 t Carbon/ha. Compared to other conventionally logged areas with 3.3% under roads the improvement is quite clear.

Guyana

Road widths differ considerably within Guyana. Some companies use very wide roads to allow sufficient drying up after rain. Primary road widths may be up to 30 wide with a total clearing of up to 60m in clayey areas (BCL 1997). The total estimated road density estimated for 1998 is 63m/ha, 45 of which is secondary roads, 18 of which is primary. With total clearing widths of 30m for secondary roads and 60 for primary this adds up to 2.13% of the area being under roads, although it can be as high as 3.8% (ECTF 1997). This would be equivalent to a loss in carbon of 3.6 t/ha. With an expected harvest of 216,000 m^3 at $14m^3$/ha in 15,000 ha this corresponds to a loss of carbon in standing biomass for 1998 of some 98,700 ton. Log markets add an additional 1% tot the standing biomass losses - 26,000 ton/year.
In central Guyana the roads on the sandy soils are often less wide - 16 and 6 for major and spur roads respectively (DTL 1996). Comparable widths are given for the concession of Case Timbers, where the area affected by roads would be just under 1% resulting in a loss of carbon of only 1.5 ton/ha. Improper road construction may lead to heavy sedimentation in low lying areas close to the road. This is often observed near stream crossings. Sedimentation may lead to forest die-back and subsequent carbon emissions.

2. reducing felling damage

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[2] Fuel consumption of buldozers at heavy load is 40l/h. A dozer will push 1km/day (8 hours = 320 l). Amount of road length was 66m/ha, equivalent to 15 kg C/ha in the diesel used.

Case studies

Table 10 shows that in all south American experiments RIL resulted in reduced damage in the canopy as well as on the forest floor. The canopy damage is important as it concerns mostly large trees and thus substantial damaged biomass. Obviously falling trees also kill small trees where they land. Skidders avoid large trees and thus the damage due to trails is mainly affecting small trees. Thus, again the biomass involved is relatively small.

Table 10. Damage in logging studies in south America.

Country	reference	harvesting method	harvest m3/ha	trails % area	gaps % area
Guyana	van der Hout (1996)	RIL	14	6	7
		RIL	24	8	15
		RIL	45	10	32
		CNV	24*	8	15
		CNV	45*	24	12
Suriname	Jonkers (1987)	semi-RIL	15	5	23
		semi-RIL	23	9	27
		semi-RIL	46	18	36
Suriname	Hendrison (1990)	RIL	18	7	7
		CNV	18	15	14
French Guiana	Schmidt 1989*	CNV	14*	10	15
		CNV	24*	12	18
		CNV	45*	17	25
Brazil	Johns *et al*. (1996)	RIL	37	6	10
		CNV	33	9	19
	Winkler (1998)	CNV	34	4	10
		RIL	34	22	24

Studies in SE-Asia show similar reductions * volumes estimated from basal area's in van der Hout 1996.

Guyana

Damage differs considerably among areas. In central Guyana one study (Hammond & Brown 1991) found that after felling for each tree felled two trees were smashed with a basal area similar to the tree felled. A study of RIL (calculated with data of van der Hout 1996, see annex 3) also suggests that damage levels, in terms of basal area, after felling are similar to the amount felled. This study further suggests that damage after skidding is 1.5 times the amount felled. In the RIL study in Guyana canopy damage was not reduced with RIL (van de Hout & van Leersum in press). It also proved almost impossible to avoid damage to potential crop trees. ECTF (1995, 1996, 1997) reports a ratio of basal area damaged to felled of 3! With damage rates over 5 not uncommon and a maximum rate found 60! There appears to be scope for improvement in some areas.

3. reducing losses

Case studies

Improved felling techniques may increase the recovery per tree. Losses due to improper felling and bucking can be quite high but can be decreased by utilising better felling techniques (Winkler 1997). Losses in Brazil were 8.5% with CNV and 3.9% with RIL, respectively (Winkler 1997). This reduction translates to a savings in losses of 0.68 m^3/ha, quite comparable to Uhl *et al*. (1997) who report a total difference of 0.75m^3/ha. This is of obvious direct economic benefit.

In conventional operations logs are often not found by the skidder operator due to poor communication. Uhl *et al*. (1997) estimate this loss to be 7m^3/ha. The carbon savings depend on the end use of the product. Whereas plywood has a residence time of 3 years only, waste in the forest has a residence time of 20 years. From a carbon point of view reducing waste in low intensity operations may not necessarily lead to carbon gains (see below).

Guyana

Directional felling with improved recovery proved very well possible in Guyana (van der Hout 1996) but actual data are not yet present. Also ECTF (1996) reports residual timber in its monitoring plots due to improper felling and bucking.

Not all logs are necessarily retrieved in Guyanese operations (pers. obs.), most likely due to poor communications. Surely the amount lost on average must be lower in Guyana than the 7m^3/ha reported by Uhl *et at*. (1997). But it could easily be that figure in those areas where 70m^3 has been felled. Losses could thus well be in the order of several percents of the felled volume.

4. reducing skidding damage

Skidding damage can be greatly reduced with the consistent use of a winch to pull the logs to the skid trail (most studies above). Although the savings in biomass due to this will be relatively small the effects on regeneration will be large. Also decomposition of organic matter may be increased due to soil exposure, which will have an (unknown) effect on the carbon balance. Apart from a reduction in biomass losses RIL also increases skidder efficiency (Table 10), decreasing cost of logs at the log market by some 20%. Although the skidding of planned RIL is far more efficient in terms of skidded volume per period of time, approximately the same amount of fuel is used per hectare to haul logs and this amount is again very small compared to the biomass components of RIL.

Table 11. Skidding efficiency in Suriname (after Hendrison 1990).

	CNV	RIL
available machine time (h)	1336	1376
effective machine time (h)	641	966
skidded area (ha)	220	322
skidded logs	1648	2754
skidded volume (m^3)	3461	6086
fuel (@15l/h)[1]	9615	14490
fuel/ha (l)	44	45
fuel/m^3 (l)	2.78	2.38

[1] Skidder CAT 525 at medium power (annex 6).

Guyana

In Guyana a comparison between skidding under CNV and RIL has been made but data were not available at this time. In terms of damage RIL reduced damage quite substantially (van der Hout & van Leersum in press). In the RIL plots damage, expressed in basal area, after felling and skidding was roughly 1.5 times that of basal area felled. There are no comparative data on efficiency. It was said at one time that RIL skidding produced twice as much volume as CNV skidding (van der Hout pers. comm.). It remains to be seen if this is difference is as large as this when actual machine time is taken into consideration (as in Table 10). Cost in Guyana is comparable to Suriname at the log market (US$ 22/m^3, Fleming 1995, see also Table 8), thus savings could be roughly equivalent.

5. utilising waste more efficiently

Utilising waste more efficiently may be an effective way to reduce losses in carbon. One example is the Pemberton Mill in Western Australia, where part of the sawmill waste is converted into wood chips, bark is converted into garden mulch and saw dust is sold to a canning factory nearby to be used as fuel (Bunnings pers. comm). Being able to utilise all waste efficiently depends on a lot of things, being close to population centres being one of them. None of the above case studies particularly targets the waste problem at the mill.

Guyana

One of the larger timber operations in central Guyana consumes 9000 gallons of diesel oil per week, 40% of which is used for the generation of power and 60% of which for transportation. If saw mill waste, which is typically 58% of log volume brought to the mill, given a recovery of 42% at this operation (DTL 1996), could be utilised for the generation of power this could result in a carbon savings of 12 ton carbon a week[3] (or at 50 weeks of operation of 600 ton), assuming sustained regrowth. In 1997, the log production delivered at this mill was 56,000 m^3, which would have produced a waste of 32,000 m^3, which at a dry weight of 0.75 would convert to 12,000 ton of waste carbon. Another 16,000 m^3 of peelers was logged and exported without further modifications. The total log production of this company was thus 73,000 m^3 in 1997 (1995: 22,000; 1996: 36,000). Given a rate of exploitation of between 3-5m^3/ha the area utilised (but not all logged) would be around 14,000-24,000 ha.

A gasifier was installed in the early eighties at the mill site but never worked well due to technical complications. New plans have been discussed to install a steam turbine at the site. At least one company is operating with a steam plant, which has been working well for a long time (J. Willems pers. comm.). This company, being close to Bartica, is also able to sell of more of its waste to nearby residents, including slabs for waterfront linings.

Whereas transporting low-grade materials from the interior to the coast for cheap timber may not be economically feasible but with an added carbon credit of US$ 10m^3/ton carbon it might be worth considering.

In the following an attempt will be made to quantify the effect of harvesting on the carbon stocks in Guyana's forest. Also an attempt will be made to quantify the effect of RIL in the Guyanese context. Before we can do this first we will develop a model describing the carbon pools and fluxes in the forest ecosystem. This will be done in 4.3.

4.3 A simple carbon model

4.3.1 The model

The main components of a standard simple carbon model are given in Figure 4.

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[3] =3600 gln * 4.5l/gl * 0.9 (spec. dens.)* 0.8 (carbon content)

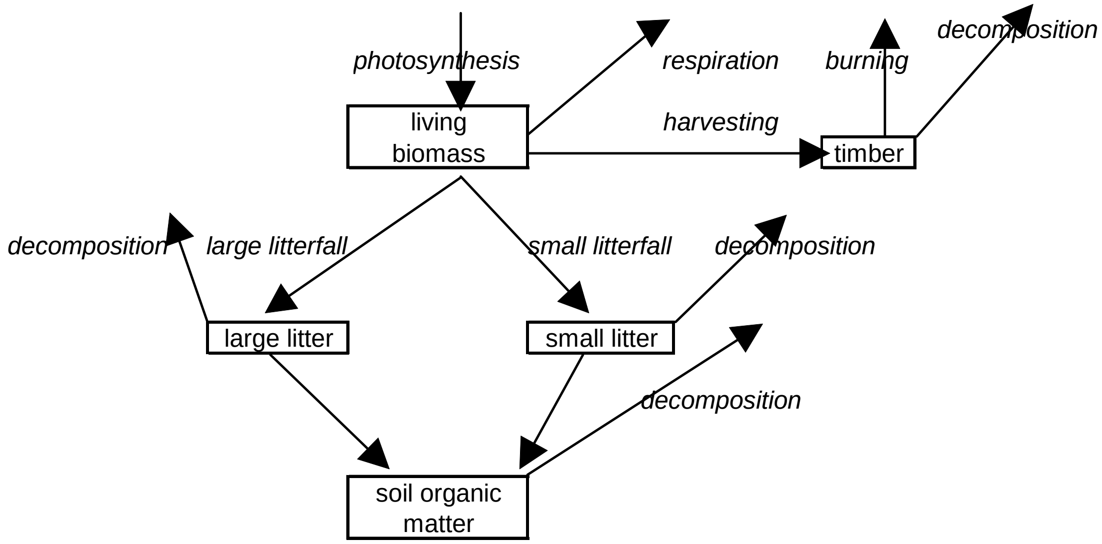

Figure 4. Simple carbon model for a forest ecosystem.

This model is not unlike that of Dewar (1991) or that of Nabuurs & Mohren (1993)

The assumptions for the model are as follows:

1. Aboveground biomass is 275 t/ha (average of mixed forest on brown sand and loam, Table 6)
2. Aboveground biomass has a fixed partitioning: stems 68% (187 t/ha), branches 30% (82.5 t/ha) and leaves 2% (5.5 t/ha) (chapter 2.1)
3. root biomass is a fixed 22% of aboveground biomass, 60.5 t/ha (chapter 2.1)
4. total biomass is thus 335.5 t/ha
5. small litter is equal to leaf biomass (5.5 t/ha)
6. annual small litter production is equal to leaf biomass
7. residence time of small litter is 1 year[4]
8. 50% of the small litter decomposition is added to SOM, the rest is respired (G. Heil pers. comm.)
9. production of large litter (above and below ground) is 1% of standing stem and branch biomass, based on natural mortality.
10. residence time of large litter is 20 years (10 year in Nabuurs & Mohren 1993)
11. 50% of the large litter decomposition is added to SOM, the rest is respired (G. Heil pers. comm.)
12. SOC (soil organic carbon) is approximately 165 t/ha. SOM having a carbon content of 58% is thus 286 t/ha.
13. residence time of SOM is 65 years (100 y in Nabuurs & Mohren 1993)
14. Forest growth is based on simple population growth with mature phase above ground biomass at 275 t/ha (2.1) with population growth constant fixed in such a way that after a harvest of 20m^3 (with 20m^3 damage) the forest grows back to its original biomass in 50 years:

$$dM/dt = r * M * (K-M/K)$$

where M is current biomass, K is mature phase biomass (275 t/ha) and r = 0.078

---

[4] 4, 5, 6 are simplifications to ease modelling with steps of 1 year but as the total quantities of small litter are not very large the error is considered acceptable.

15. Forest at carrying capacity is neither a source of nor a sink for carbon.
16. At harvest: the amount of biomass damaged (due to felling) is equal to that of the basal area harvested in some operations (calculations based on: Jonkers 1987, Hammond & Brown 1991, van der Hout 1996) and 1.5 times as high after skidding (16 trees/ha, appr. 45m^3/ha, van der Hout 1996). In other operations the basal area damaged (after skidding) can be as high as three times that of the basal area harvested (ECTF 1996, 1997, 1998).

Ad. 10: Nabuurs and Mohren (1993) give a residence time of large woody debris in the forest of SE Asia of 10 years. There is consensus that the high-density stems of Guyana's forest may take a very long time to decompose. After 20 years, however most signs of a logging operation appear to have vanished, thus the residence time of 20 years. The model will be tested as to the effects of this change.

Ad. 13: Using a SOM residence time of 100 years (Nabuurs & Mohren 1993) and running the model without harvesting resulted in a equilibrium quantity of SOM of 445 t/ha, which is far higher than observed. To obtain acceptable SOM quantities SOM residence time was set at 65 years, which resulted in a SOM stock of 176 t/ha, much closer to the observed value. The lower residence time is consistent with turn-over estimates of deep soil carbon in the range of 25 years found by Trumbore *et al*. (1995, cited in Fearnside & Barbosa 1998). SOM dynamics is really a problem at present and "*The IPCC has, so far, not encouraged inclusion of carbon fluxes from soils under cleared tropical forests in the national inventories now being compiled under the framwork of the FCCC…….There is no scientific consensus on whether clearing land leads to significant soil carbon loss in tropical forest*" (Fearnside & Barbosa 1998). However, with the production of large litter as a result of logging excluding SOM (and large litter for that matter, as the dynamics of this compartment have also been largely ignored) would invalidate any model.

Ad. 14: Research in Suriname (de Graaf 1986, Jonkers 1987) suggest that forest is capable of recovering of a 20 m^3/ha and a further refinement of 20m^3/ha in 20 to 25 years, assuming that treated forest will grow at 2m^3/ha/y. Untreated forest is shown to regrow at some 1m^3/ha/y, thus recovery of a harvest of 20 m^3/ha with an additional identical damage in some 50 years seems safe. This is further supported by data of Saldarriaga (1994), which show that forest regrowing on slash and burn sites is capable of attaining a biomass of 80% in 60-80 years. Obviously, the quality of this regrowing forest may in no way resemble to original forest. This is the same problem we are facing here. Due to harvest the forest composition will change to some extent (with lighter timbers likely) but we have at present not enough data or accurate models to predict this change properly. Because recent studies in Indonesia have shown that model based forecast of cutting cycles have been too optimistic we will also run (worse case) scenarios with a biomass recovery in 70 rather than 50 years.

Ad. 15: The model assumes that a forest in equilibrium is neither a sink for nor a source of carbon but this may but may not be necessarily true in practice (Lugo & Brown 1992). In fact, Amazon forest has been shown to have a net carbon gain of approximately 1 t/ha in 1992-1993 (Grace *et al*. 1995a,b.). However, the period of measurements in this study was relatively cool and a warm year would result in less sinking effect due to the fact that respiration rises much more with increased temperature than does photosynthesis (Grace *et al.* 1995a).

4.3.2 A sensitivity analysis of the model

A number of assumption have been made to make sure that the carbon model produces acceptable stocks of SOM in the ecosystem. The model is likely to be sensitive to changes in relative fluxes towards SOM and its residence time, for which proper data is greatly lacking. We have also made assumptions on regrowth and will test the models sensitivity to a slower growing forest. We will also test the effect of large litter residence and product life.

But before we do this we will first look at the long-term effect of one single harvest of 40m^3 of plywood timber, with a damage twice that of logging. This will enable us to see the where carbon moves in the different compartments of the model. The results of this harvest are given in annex 4.

Because of the relatively high harvest a considerable reduction of biomass is achieved after harvest (A). However, right after the harvest all carbon is still present in its pre-harvest form but in a different condition. After harvest the forest biomass returns to near original state in approximately 67 years (figure A). Product decay outside the is fast (plywood) but inside the forest log residence time is 20 years and part of it is incorporated in SOM, where it will remain for an even longer period. Thus the model predicts a lag in decomposition as compared to forest regrowth.

There is a net carbon loss starting after logging (B,C). This loss is caused by the fast decomposition of small litter and fast product turnover. When waste is burnt, rather than left, a huge burst of carbon (appr. 10 t/ha) enters the atmosphere shortly after logging (in fact after sawing). The carbon losses increase to 23 t/ha soon (year 7), because of the short life of the end product and the burnt waste. Not burning the waste but allowing it to decompose slowly results in a lower peak loss of only 15 t/ha, saving 8 tons at peak value. Since decomposition of large litter, partly through SOM, in the forest takes longer than forest regrowth, is there a net carbon gain after 30 years, which peaks at 6.6 ton/ha (if waste materials are not burnt) around 61 years after logging. This gain would be twice as large if a longer product life would be achieved but is not influenced much if waste is burnt of left. Using waste as fuel reduces the carbon emissions even a bit more. There could be a lasting reduction in carbon emissions in the order of 10 to 15 tons.

After 300-400 years when all material has decayed the system returns to its original state with no carbon gains or losses. Thus the effects of one harvest are temporary on the long run.

To achieve continuous gains through forestry activities the balance of harvesting, damage and product life time should be such that a continuous stock of products is available outside the forest and SOM in logged forest is permanently higher than in natural forest. There must be limits to this.

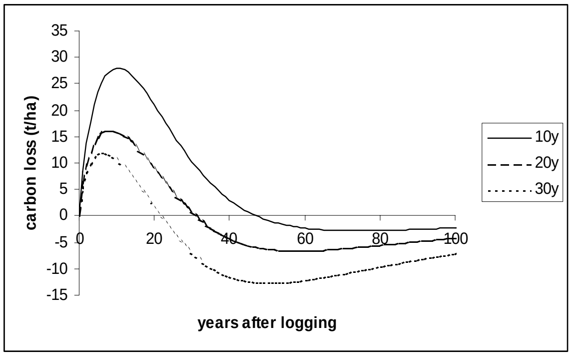

Figure 5. Changes in large litter residence influence the carbon-offset.

How sensitive is such a model to changes in its assumptions?

1: Large litter residence time

Large litter residence time in Guyana is set at 20 years. With an annual input of large litter, equal to dying biomass (1%) a reasonably large litter stock of 54 t/ha will build up. In addition to 20 years, the carbon model was tested with a residence time of 10 years (Nabuurs & Mohren 1993) and 30 years (very high) with again a harvest of 40m^3 of plywood timber. The large litter stock that will accompany these changes are 27 (reasonable) and 81 (very high), respectively. The results are give in figure 5. A change from 20 to 10 years changes the forest the net emissions drasticaly (from 15 t/ha to nearly 30 at peak). This is due to the fact that higher emissions from decomposing large litter are added to the decomposition of small litter and the product. It is thus very important to have this figure right. Because Greenheart logs are very resistant, a decay in twenty years or more is not unreasonable. However, for peeler species, such as Baromalli, decay may in fact be much faster.

2: SOM residence

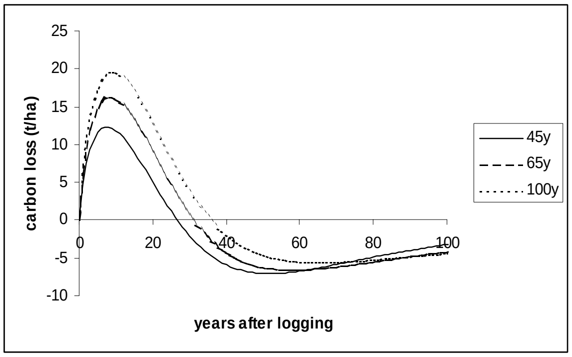

Figure 6. Changes in SOM residence influence the carbon-offset.

SOM residence time is estimated at 65 years. Some SOM may actually turn over at time-scales of 25 years (Trumbore *et al*. 1995) other SOM parts may be practically stable (charcoal in the soil may have an age of over 2000 years, D. hammond & ter Steege unpublished data). To assess the sensitivity of the model to changes in SOM residence SOM residence was tested at 45, 65 (default) and 100 (Nabuurs & Mohren 1993) years, again with a harvest of 40m^3. To allow for reasonable SOM quantities the percentage of litter being decomposed into SOM has to be changed together with the SOM residence. Percentages that result in the expected SOM of 176 t/ha are: 72% (unrealistically high!), 50% (default), and 32.5% respectively. Figure 6 shows the result of the three simulations with a harvest of 40m^3/ha of plywood timber. Whereas the amounts of carbon loss (both positive and negative) differ in their amounts, the peaks of net emission and sequestering are around the same time. Differences in net sequestering are in the order of 5 t/ha respectively. A large change considering the total effect. Thus the model is quite sensitive in sequestering quantities for varying SOM residence time but not so much in the timing of losses and gains. Because many carbon contracts are for short term purposes and are likely to be the result of reducing damage than sequestering in SOM, the effects of changes in SOM turnover may not be that important. At low harvest the differences are very small between the three SOM turnovers.

3: Product life

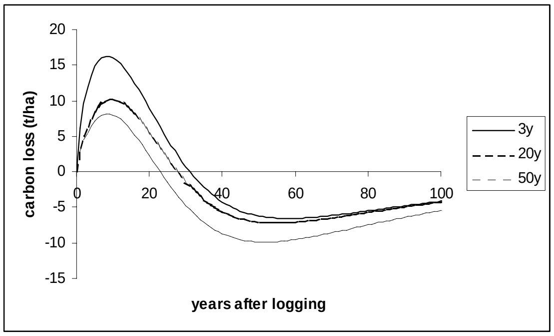

Figure 7. Changes in product lifetime influence the carbon-offset

Table 12 lists some average residence times of timber products. Plywood has a fairly short life time (estimated turnover time is 3 years, Nabuurs & Mohren), other products may have much longer life. Furniture has a far higher expected lifetime and marine timber is known to resist decay in temperate water of at least a century in many cases. Since decaying products add carbon to the atmosphere the timing of the decay will have an influence on the net carbon budget of our harvest. The results of a simulation with 40m^3 of timber with three expected life times (3, 20, and 50 years) are given in Figure 7. The effect of increased product life is less drastic as changes in large litter decomposition, because the quantities involved are approximately 20% of the quantities of large litter (large branches and roots are left in the forest as large litter, damage equals harvest, 45% conversion at the mill). With a product life of 3 years we experience carbon emissions after 3 years of logging that are about 5 t/ha higher than with a product life of 50y. This difference remains high until appreciable amounts of the product with a lifetime of 50 years have disappeared. With smaller harvest (15m^3/ha), there is hardly any difference between the carbon emissions for the different product lives. At high harvest however: the longer the product life the more sequestering. (model results not shown).

Table 12. Average residence time (y) of wood products

product	Energy wood	Paper wood	Packing wood	Particle board	Sawn timber	Marine timber
residence time (years)	1	2	3	20	35	100

Data from Nabuurs & Mohren (1993), Marine timber estimated on records from the UK and Netherlands

4. Forest growth

Forest may grow back a little less fast than assumed in the model, which is moderately positive. Research in SE-Asia has recently shown that realised regrowth on research plots stayed far behind predicted growth (D. Cassells pers. com.). This was also the case in French Guiana (S. Gourlet Fleury pers. com.). The model was tested with a change in growth of a slightly less than 1m^3/ha/y to 0.5 m^3/ha/y (r = 0.039). The effect of these changes is dramatic (Figure 8). But then the 1m^3/ha is already only moderately positive, as the CMS forecasts 2m^3/ha for treated forest. Forest regrowing at half the estimated rate will never net sequester carbon, whereas forest regrowing at 2m^3/ha/y will sequester close to 35 t/ha at 20 years, compared to only 5 t/ha (at 31 years) for forest with average growth. Again the carbon model is very sensitive to changes.

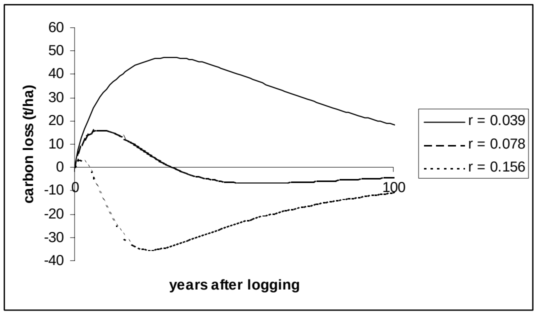

Figure 8. Changes in forest growth influence the carbon-offset greatly.

Whereas the final product of a timber concession is known to some extent, data on large litter and SOM turnover are scarce. Without more data we will use the best guess estimates as given above but we have to realise that considerable changes in the results may be possible but mainly at the longer run. Modelling without the inclusion of large litter and SOM, however, will result in even less realistic estimates.

There are now two main scenarios that are relevant to Guyana.

Scenario 1 is a logging operation in the ‘Greenheart belt’ of Guyana with a main emphasis on Greenheart and an average logging intensity of 5m^3/ha but concentrated in commercial patches where logging intensity is a good 50m^3/ha. Logging damage is roughly 1.5 times the felled volume (annex 5). The timber is converted into construction timber (high product residence, table 8) with a recovery rate of 42%. The company aims at a rotation cycle of 25 years (DTL 1996). Area under roads is fairly small, typically less than 1%, which we will take as an average. Log markets add another 1%. Due to poor communication a certain percentage of the felled trees may not be recovered and due to poor sawing and bucking the recovery in the forest is lower than possible.

Scenario 2 is a logging operation in the sub-coastal zone of the north west of Guyana producing 14m^3/ha (ECTF 1995, 1996, 1997), which is converted into plywood (low product residence, table 8) with a recovery rate of 50% (Nabuurs & Mohren 1993). Damage due to the harvesting operation is three times the felling intensity (based on ECTF 1995, 1996, 1997) and roads and markets cover some 3% of the area (ibid.). Due to poor sawing and bucking the recovery in the forest is lower than possible (ibid.).

Each company has three choices for its waste:

1. burning quite soon after sawing, which is current practice at most companies
2. utilising the waste to produce energy for the saw mill and nearby housing facilities
3. leaving the wood to decompose slowly

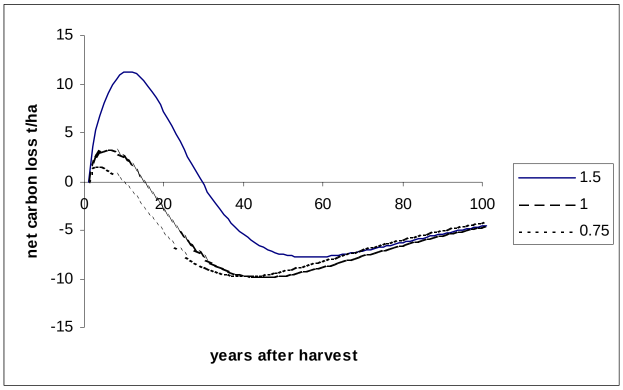

Figure 9. Damage reduction reduces carbon emissions in Greenheart harvesting.

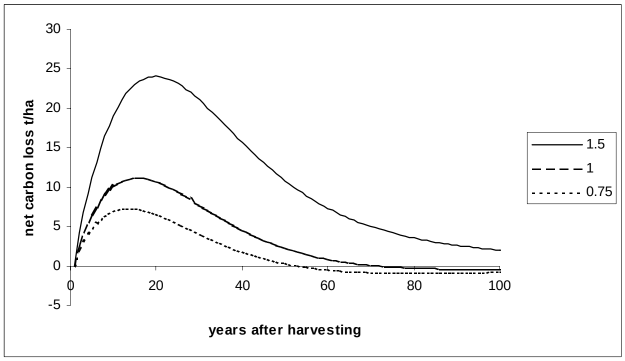

Figure 10. Lower growth results is higher offsets when reducing damage.

For each of the companies we will develop a most likely case scenario (from a carbon point of view) based on the assumptions set out above, a worst case scenario with 25% less growth, faster decomposition of large litter, faster turnover of SOM and a best case scenario with 25% faster growth slower decomposition, and slower turnover of SOM.

Scenario 1: The results of scenario 1 are given in annex 5. The forest returns to 99% of its original biomass after 75 years. Due to this long recovery needed a second harvest at 25 years is unrealistic and no further rotation cycle is applied. Due to the high harvesting level the total harvested and damaged volume is considerable (ter Steege *et al*. 1996, Zagt 1997) and the forest is a source for carbon for several years after harvesting.

The high harvest resembles harvesting practices of SE-Asia in terms of percentage felled and damaged and reduction of damage due to harvesting will also results in carbon gains. This is shown in Figure 9. A reduction in damage from 1.5 to 1 results in a carbon gain of some 7 to 8 tons per ha forest logged. In areas where 70m^3/ha is being harvested, the gain can be up to 15 ton/ha (data not shown). With forest growing 25% less fast the forest will never sequester net carbon and the differences in carbon loss are larger in the first years (Figure 10). Differences in carbon would be larger. Looking at fluxes rather than net carbon losses, both systems are a source of carbon in the first years after harvesting. Reducing felling damage can lower this flux. As can be seen in Figure 11. Over a carbon project life of twenty years the difference would sum up to a 172 t/ha if damage were to be reduced by 50%. However, preliminary results of a low impact harvesting study in Guyana showed that this may not be feasible. The total harvest of Greenheart in Guyana is some 500,000 m^3, which if we assume is harvested at a 50m^3/ha rate is equivalent to 10,000 ha. At a cost of US$ 10 per ton carbon the total savings for a twenty-year project (assuming constant harvest each year) would result in US$ 17 mln.

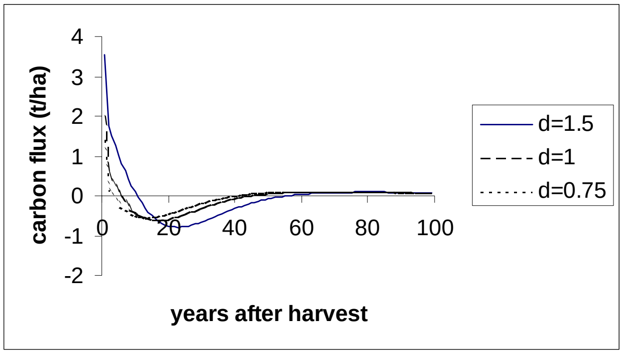

Figure 11. Yearly carbon fluxes after a heavy harvest.

Scenario 2: The results of scenario 2 are given in annex 6. The forest returns to 94% of its original biomass after 25 years, at which time a 2nd harvest is applied. At the long term biomass settles at a slightly lower value after several harvests (270 t/ha, a 17% loss), while at the same time SOM averages 339 t/ha, which is considerably higher than that of natural forest (286 t/ha). The product life of plywood is short thus carbon savings through the product are small. There are long term carbon gains if this harvesting system could be sustained. Reduction of losses does not result in a reduction of carbon emissions due to the relatively low harvesting impact. The total very long-term (200 years) carbon gains of this scenario would be in the order of 20 t/ha.

Both scenarios thus show that the prospects of carbon gains in Guyana are relatively small.

In both scenarios a continuous carbon gain can be achieved by utilising waste for the generation of energy, rather than utilising fossil fuel. As has been calculated above also these gains are relatively small.

5. Recommendations for further research

There is no data on the production of large litter, its standing crops, and residence time in Guyana. This hampers a proper implementation of carbon models. Even more needed is reliable data on SOM quantities and turnover. We are now relying on the data of just a few studies. Since SOM quantities can be potentially large and have a possible long turnover time these are very important parameters.

Saving fossil fuel at the mill site by utilising waste as biomass fuel may be a possibility to reduce emissions. The set up of steam turbines financed through carbon credits may be well worth pursuing. At a later stage such steam turbines may even provide power to the national power grid.

Mills in Guyana have a relatively low conversion rate of between 40 and 50%. Improved machinery and training may possibly reduce the losses incurred here.

Dakama is widely used as fuel in bakeries around Georgetown, although many bakeries may convert to gas in the near future. Wise utilisation of Dakama forests would be preferable to such change to fossil fuel. However, due to harvesting the forest will become even more fire prone than it already is. The combustion of litter alone would cause a carbon emission of close to 40 ton per ha in well-developed Dakama forest. Fire has also been observed in a logged area in central Guyana during the 1997-1998 el Nino drought.

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Annex 1.

Equations to calculate biomass component of Amazonian forests.

French Guiana, Lescure *et al*. (1983):

	leaves	branches	woody parts
Dw(kg)=	$.00873D^{2.1360}$	$.04585D^{2.7098}$	$.04863D^{2.7632}$
Dw(kg)=	$.00017(D^2H)^{0.7587}$	$.00096(D^2H)^{0.9759}$	$.00031(D^2H)^{0.9759}$

Total Dw(kg)= $.05653D^{2.7248}$ <- formula used

Total Dw(kg)= $.00039(D^2H)^{0.9626}$
where D is diameter at breast height (cm), H is height in cm. The functions returns dry biomass in Kg.
[Note the highlighted formula is most likely wrong]
Based on 914 trees. $0.92 < r < 0.98$.

H can also be calculated as a function of D:
$H = 249\ D^{0.6985}$. ($r = 0.92$)

Suriname, Jonkers (1987):
Biomass stems (kg) = $1.1184(10^{(-3.4853 + 2.5132 \log(D))})$
Biomass branches (kg) = $1.4428(10^{(-4.8516 + 2.8368 \log(D))})$
Biomass leaves (kg) = $1.1184(10^{(-3.7644 + 1.9961 \log(D))})$
Number of trees and r unknown.
where D is the diameter at breast height (mm). Biomass is returned as dry weight in kg.

Brasil, Russell 1983:
Aboveground = $e^{(0.9825 * \ln(D*D*H*\delta) - 2.8265)}$
Belowground = $e^{(01.2368 * \ln(D*D) - 3.1289)}$

where D is diameter, H is height, δ is wood density.
Based on 13 trees, $r = 0.99$. Wood density in Jari is 0.630 g/cm^3.

H was best described as a function of D by:
$H = e^{(0.7128 * \ln(D) + 0.8858)}$
Based on 47 trees, $r = 0.95$.

Venezuela, Saldarriaga 1994:
above biomass (kg) = $e^{(-1.086 + 0.876\ln(D*D) + 0.604\ln(H) + 0.871\ln(\delta))}$
where D is diameter, H is height, δ is wood density.
Based on 39 trees, $r = 0.92$.

Radambrasil
stem volume is $\pi r^2 h * 0.7$ as used by Radambrasil.
H is **bole** height
Tree biomass is $100/68 * \delta * V$

Annex 2.

Tree aboveground biomass estimates (t/ha) based on basal areas of Forest Industries Development Survey per inventory zone and forest type. Biomass calculated according to Lescure *et al*. (1983).

	Zone	1	2	3	4w	4e	5	6	7l	7h	8	9n	9s	10
	mixed forests on …… terrain													
1	undulating to hilly	303	267	276	356		267	186	312			285	150	303
1b	flat to undulating	285		312				168				222		294
1c	deeply dissected, steeply sloping		303	276			267	177				338	213	303
1d	liane forest													
1e	flat to undulating					258		177			132			
1f	undulating to hilly	356												
1g	hilly broken	356							303					
1h	high hills	392		276	590	213			374	321				
1k	low mixed, laterite													
1l	flat to undulating		150											
1m	small crowned, flat to undulating													
1p	on shallow rocky soil									141	123			
2	Clump walaba forest													
2a	Wallaba forest	365												
2b	Clump walaba forest	267												
2c	Wallaba-Dakama forest													
2d	Dakama-Muri scrub													
3	low swamp forest						195							
3a	river levee forest													
3b	Mora forest				356		240	195						
3c	marsh swamp forest												123	
3d	low open swamp forest													
3e	Swamp forest on pegasse													
4	mangrove													
4a	low open mangrove													
1c/3													267	
1f/3c													312	
1g/3c														
clearings														
open swamp														
rivers, islands														
clouds														
savannah														

zones: 1 Mazaruni-Kuribrong;2 Waini-Cuyuni; 3 Cuyuni-Mazaruni; 4w Essequibo-Corentyne, west of Essequibo; 4e Essequibo-Corentyne, east of Essequibo; 5 Amakura-Waini; 6 Middle Essequibo-Rewa; 7l Pakaraimas lowland; 7h Pakaraimas highlands; 8 Rupununi;9n Upper Essequibo north of Kassikkaitu ; 9s Upper Essequibo south of Kassikkaitu; 10 New River.

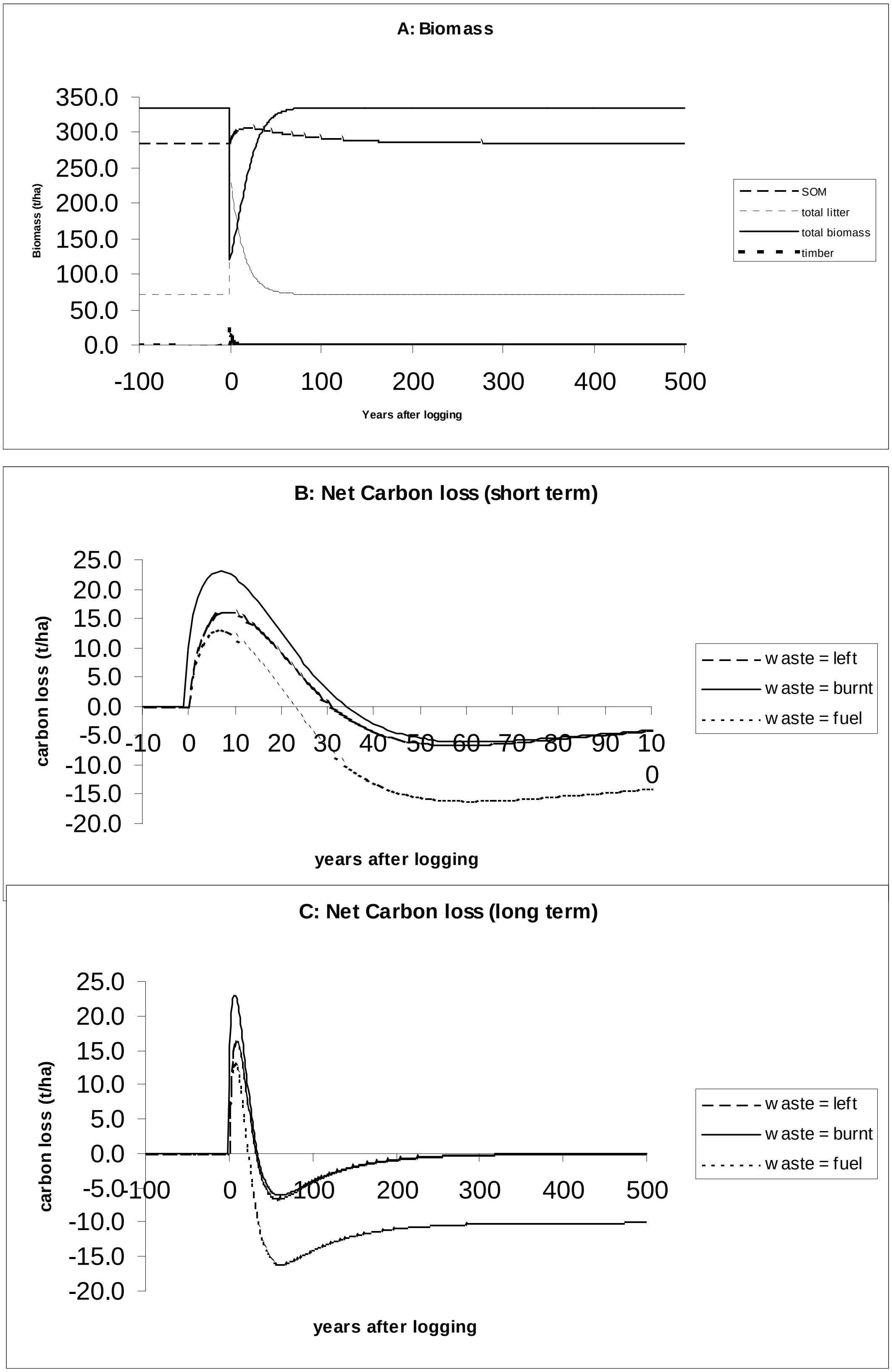
Annex 3

Original basal area (m^2/ha) and basal area felled and damaged after felling and skidding in a RIL study in Guyana (based on data of van der Hout 1996).

AFTER FELLING		BA	BA	BA	BA
DBH mid	Trees/ha	original	felled	destroyed	very severe
4 trees/ha					
5-20	836.0	10.26	0.00	0.49	0.29
20-40	151.0	10.67	0.00	0.34	0.20
40-60	36.0	7.07	0.45	0.10	0.10
>60	12.7	6.38	0.96	0.00	0.00
Total	1035.7	34.39	1.41	0.93	0.59
8 trees/ha					
5-20	810.0	9.94	0.00	0.58	0.43
20-40	150.3	10.62	0.00	0.54	0.38
40-60	38.8	7.62	1.11	0.13	0.17
>60	12.5	6.28	1.22	0.07	0.03
total	1011.6	34.47	2.33	1.32	1.01
16 trees/ha					
5-20	812.0	9.96	0.00	1.29	1.01
20-40	130.3	9.21	0.03	0.79	0.72
40-60	42.7	8.38	2.72	0.34	0.21
>60	9.7	4.88	1.08	0.05	0.15
total	994.7	32.43	3.83	2.47	2.08
AFTER SKIDDING					
4 trees/ha					
5-20	836.0	10.26	0.00	0.92	0.43
20-40	151.0	10.67	0.00	0.35	0.21
40-60	36.0	7.07	0.42	0.10	0.10
>60	12.7	6.38	0.96	0.00	0.00
total	1035.7	34.39	1.39	1.37	0.74
8 trees/ha					
5-20	810.0	9.94	0.00	1.59	0.77
20-40	150.3	10.62	0.00	0.55	0.46
40-60	38.8	7.62	1.11	0.13	0.20
>60	12.5	6.28	1.22	0.07	0.03
Total	1011.6	34.47	2.33	2.34	1.45
16 trees/ha					
5-20	812.0	9.96	0.00	2.36	1.15
20-40	130.3	9.21	0.03	0.79	0.76
40-60	42.7	8.38	2.72	0.34	0.23
>60	9.7	4.88	1.08	0.05	0.15
Total	994.7	32.43	3.83	3.55	2.28

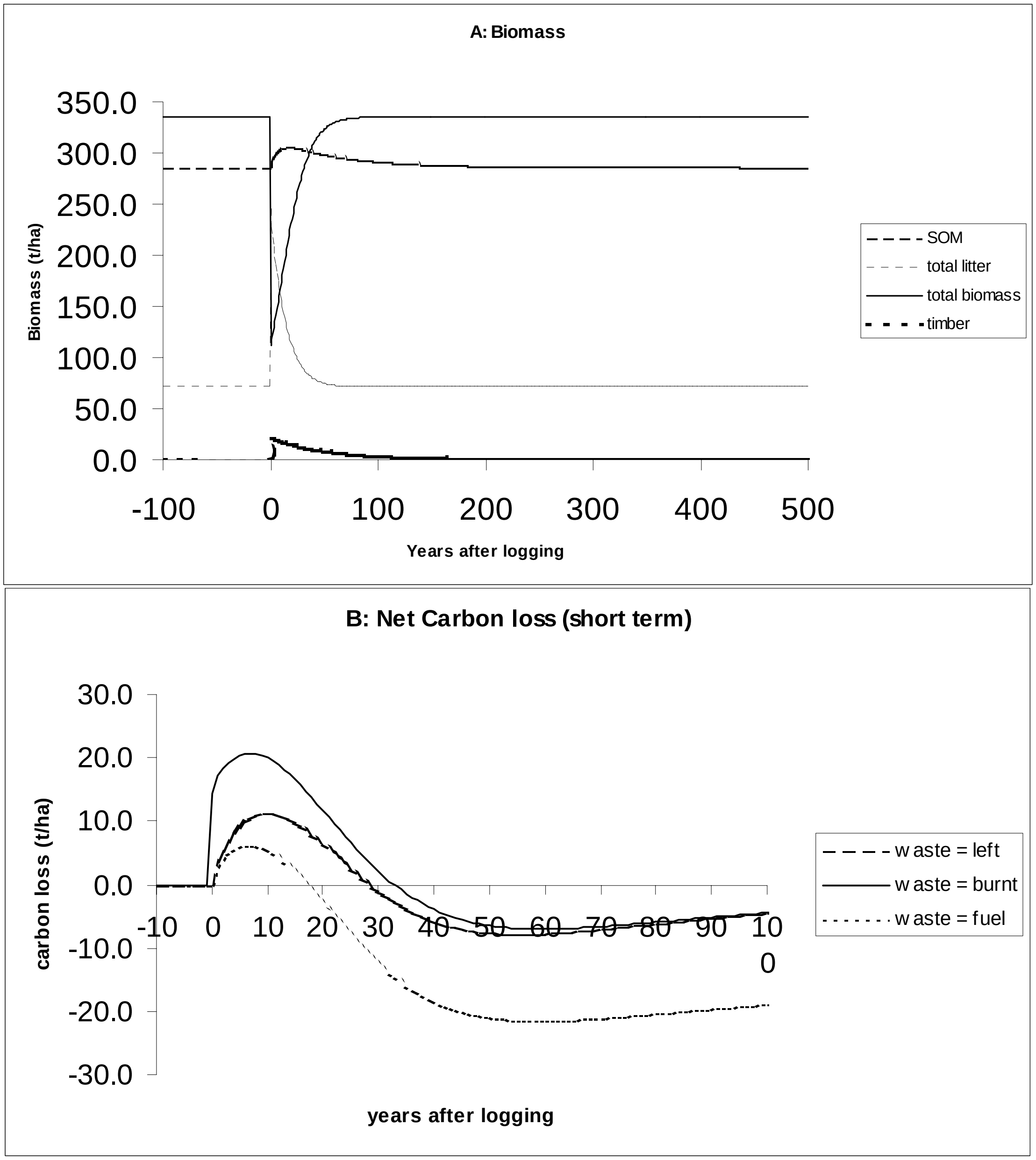
Annex 4

Results of a single harvest of 40m^3/ha, with product residence of 3 years (plywood).



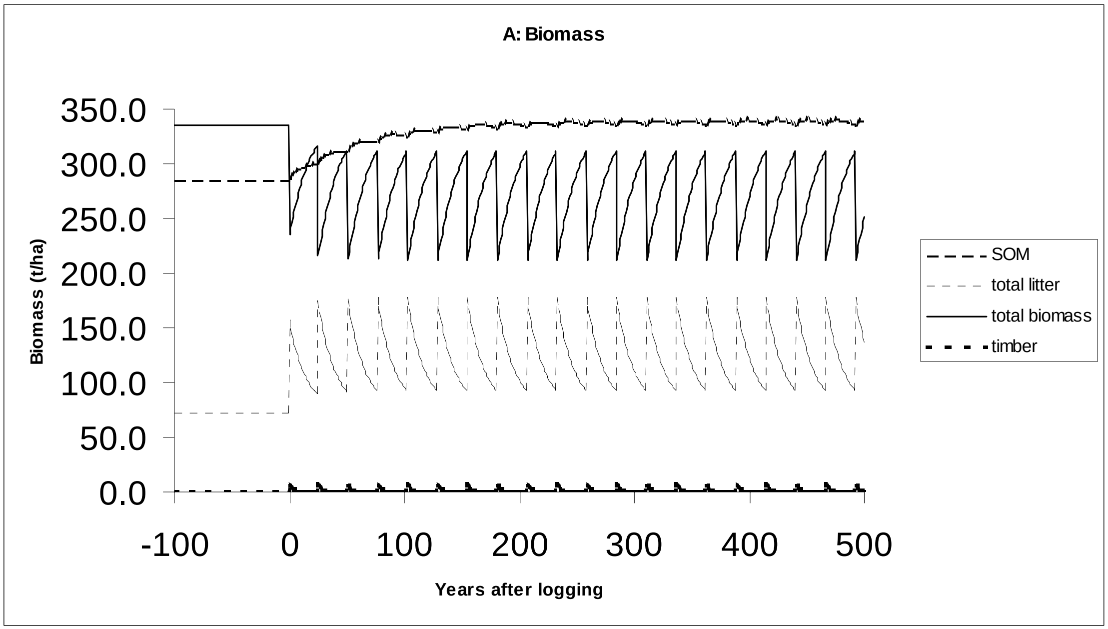
Annex 5.

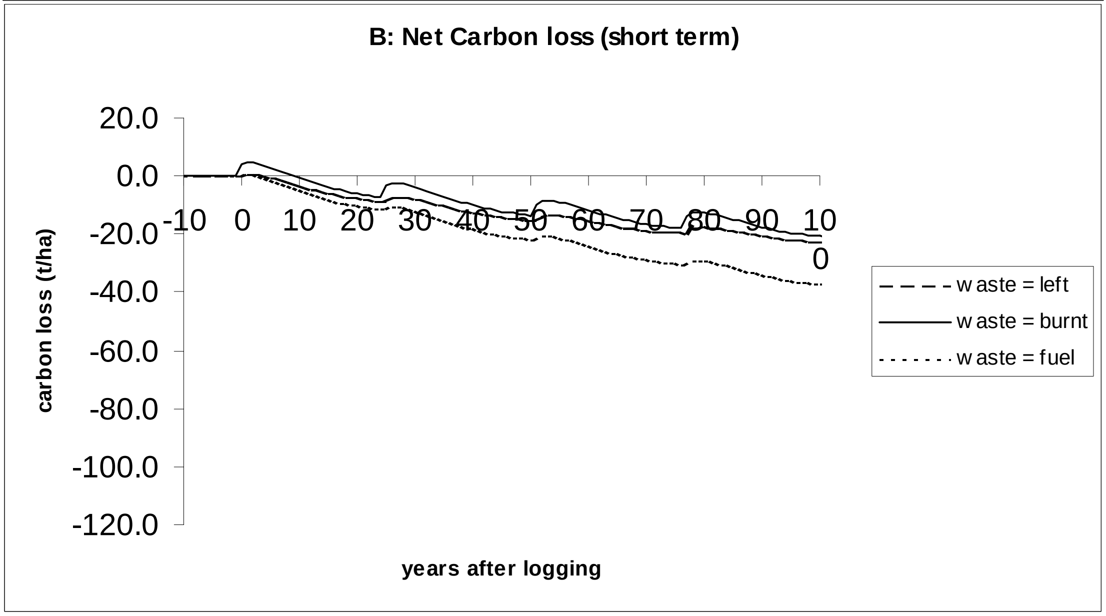
Model run of scenario 1: 50m^3/ha, long product life (marine timber).



Annex 6.

Model run of scenario 2: 25m^3/ha each 25 years, short product life (plywood).





Annex 7.

Heavy machine performance data and carbon equivalents of fuel products

A: Hourly fuel consumption tables (in litres/h) of Caterpillar skidders and dozers (source Caterpillar Performance handbook).

Skidders[1]	Low	Medium	High
515	9-12	12-16	16-22
525	10-14	14-18	18-25
528B	13-19	19-23	23-28
D4H TSK	7-12	12-17	14-19
527	14-19	19-24	24-32
Buldozers[2]			
D4E	6-10	10-13	11-15
D5B	10-13	11-17	15-21
D6G	11-21	16-21	23-29
D7G	19-25	26-34	32-40
D8R	23-28	28-38	38-51

[1] :High = Skidding heavy loads in steep terrain with high skidding resistance; medium = skidding heavy loads in moderately steep terrain with average skidding resistance; Low = skidding light loads in falt terrain with low skidding resistance.

2: High = Steady ripping, shuttle pushloading and downhill dozing, little or no idling; Medium = production dozing, pulling scrapers, most pushloading, some idling, some travel at no load; Low = considerable idling or travel at no load.

B: Specific density and carbon percentage by weight of biomass components and fossil fuel (sources: several publications and internet pages).

Material	specific density	carbon % by weight
wood	0.3-1.1	50
SOM	?	58
coal	?	75
crude oil	0.95	85
diesel oil	*0.90*	*80*
kerosene	0.79	?
gasoline	0.72	?
natural gas		52