CARBON SEQUESTRATION AND TRACE GAS EMISSIONS IN SLASH-AND-BURN AND ALTERNATIVE LAND USES IN THE HUMID TROPICS

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ASB CLIMATE CHANGE WORKING GROUP
FINAL REPORT, PHASE II

October, 1999
Nairobi, Kenya

This report is one of a series detailing results from the Alternatives to Slash-and-Burn (ASB) Programme, a system-wide initiative of the Consultative Group on International Agricultural Research (CGIAR). The ASB programme, initiated in 1994, seeks to reconcile agricultural production and development with mitigation of the adverse local and global environmental effects of deforestation. Research sites are located in humid tropical forest margins in Cameroon, Brazil, Peru, Indonesia and Thailand. The global coordination office is located at the headquarters of the International Centre for Research in Agroforestry (ICRAF).

Editor: Polly Ericksen
Cover Design: Damary Odanga
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Printed October, 1999. Please do not cite this report without permission of the authors.

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CARBON SEQUESTRATION AND TRACE GAS EMISSIONS IN SLASH-AND-BURN AND ALTERNATIVE LAND USES IN THE HUMID TROPICS

SUMMARY

The overall objectives of the Climate Change Working Group during Phase II of the Alternatives to Slash-and-Burn Programme (ASB) were to determine those land-use systems that sequester more carbon and reduce trace gas emissions. The research consisted of three activities:

1 Collect strategic information on changes in carbon stocks and land use,
2 Develop a database on trace gas fluxes from different land-use systems, and
3 Assess land rehabilitation techniques for increasing carbon sequestration.

These activities were conducted through a collaborative effort involving numerous international and national partners. Research at the benchmark sites was done by EMBRAPA-Acre, EMBRAPA- Rondônia, CENA and ICRAF- Perú in Brazil; IRAD in Cameroon; and CRIFC-AARD, ICRAF, BIOTROP-GCTE Impact Centre Southeast Asia, and University of Brawijaya in Indonesia. In addition, ICRAF and INIA in Perú conducted crucial research on trace gas emissions. Modeling activities were led by Colorado State University. TSBF led the Climate Change Working Group and assisted with the design of standardized protocols, training, field measurements and the global synthesis.

The main findings from these research activities are as follows:

1. Time-averaged above-ground carbon stocks in slash-and-burn and alternative land-use systems:

System	**Carbon (tons (c ha^{-1})**
Primary forest	300
Logged forests	100 –200
Shifting cultivation (25 year rotation)	88
Permanent complex agroforests	90
Complex agroforests (25 –30 y rotations)	40 – 60
Tree plantations	11 - 61
Crop-short fallow (<5 yrs)	5
Pastures and grasslands	3

2. Carbon accumulation rates of fallows ranged from 3.9 to 8.5 tons (t) C ha^{-1} y^{-1} compared with 3.0 to 3.6 t C ha^{-1} y^{-1} in complex cacao and rubber agroforests, and 6.0 to 9.3 t C ha^{-1} y^{-1} in the simple agroforestry systems, industrial timber plantations, and oil palm plantations.

3. Relative soil carbon values (0-20cm depth) for land-use systems compared to undisturbed forests were measured as follows:

Agroforestry systems	80-100%
Pastures	80%
Long term crop/fallow	90-100%
Short term crop/fallow	65%

- Degraded grasslands 50% or less

4. The potential for C sequestration in the humid tropics is above ground, not in the soil. Through the establishment of tree-based systems on degraded pastures, croplands, and grasslands, the time-averaged C stocks in the vegetation increase as much as 50 t C ha^{-1} in 20 to 25 years, while soil stocks increase only 5 to 15 t C ha^{-1}.

5. Improved fallow systems or improved pastures do not increase time-averaged carbon sequestration substantially from the more common short fallow and degraded pasture systems.

6. New allometric equations being developed to estimate tree biomass may result in tree biomass and C accumulation rates almost half those presented in this report.

7. Monthly N2O fluxes range from 5 to 25 ug N m-2 hr-1 in several land-use systems in Perú. The overall mean flux, 12 ug N m-2 hr-1, for the six months does not indicate any significant differences among the land-use treatments, including a forest system.

8. A net efflux of methane (8 ug C m-2 hr-1) was measured over six months in a high input cropping system in Perú. Other land-use systems had net methane consumption, from 30 ug C m-2 hr-1 in forest fallows and agroforestry systems to 20 ug C m-2 hr-1 in low input cropping systems.

9. Most of the net radiative forcing from land-use change over a 25-year period in Indonesia was from the initial loss of CO_2 from deforestation, not from the effects of N_2O and CH_4. This result may be different in intensive systems where N fertilizers are applied. There are no estimates from such systems in ASB.

STRATEGIC INFORMATION ON CHANGES IN CARBON STOCKS AND LAND-USE

The role of tropical forests in the global carbon (C) cycle has been debated over the past 20 years, with several estimates of its contribution to the increase in atmospheric carbon dioxide (Houghton et al., 1987; Detwiler and Hall, 1988). Today there is general agreement, based on land-use change data and atmospheric data, that the tropics are a net source of C to the atmosphere, in the range of 1.1 to 2.1 Pg C y^{-1} (Houghton, 1997). The primary cause of this net source is deforestation in the tropical zone, with Asia and Latin America accounting for over 80% of the flux (Houghton, 1997). The net CO_2 flux is a result of land-use change and depends on how quickly land uses are converted, the biomass of the vegetation that is cleared, the fate of the carbon cleared, the biomass of new vegetation, the time course of the subsequent land-use systems, and the regrowth rates of vegetation. Much of the uncertainty in the values of CO_2 flux from the tropics is a result of inadequate estimates for these parameters (Houghton, 1997). In particular, there is little information on the carbon sequestration potential of many of the land-use systems of the humid tropics (Houghton et al., 1993).

One activity of the ASB project was to characterize the patterns of land clearing and subsequent land use at the benchmark sites and to quantify the changes in carbon stocks associated with land clearing and establishment of different land-use systems. Standardized methods were established to measure carbon stocks in the forests, the various land-use systems established following slash and burn clearing, and promising “best-bet” alternatives at the different sites (Woomer and Palm, 1994, 1998). These data were used to calculate both the immediate and longer term losses of carbon associated with slash-and-burn clearing and to identify those land-use systems or “best-bet” alternatives that sequester the most carbon.

Carbon stocks were measured in the soils and vegetation in 94 sites in the three ASB benchmark countries (Brazil, Cameroon, Indonesia) and in an additional 22 sites in Perú. The sites sampled in each country included undisturbed or selectively logged forests as the reference point; areas that had been recently slashed, burned, and cropped; and areas that were subsequently planted to pastures, tree plantations or agroforests, or areas abandoned to fallow regrowth. Details of the sites sampled are provided in Appendix 1. This dataset, compiled by the ASB benchmark team, is unique in that it provides data collected and analyzed by standardized methods across sites. In addition, the information in this dataset on the carbon stocks and carbon accumulation rates in young fallow vegetation and agroforestry and plantation systems are rare for the tropics.

A paper synthesizing the data on C stocks across sites was presented at an international meeting in Brazil, Carbon Pools and Dynamics in Tropical Ecosystems. This paper (Woomer et al., 1999) summarized the above-and below-ground carbon stocks for the different land-use types. This analysis enables calculations of carbon losses when one land-use type is converted to another. A global summary of the total system carbon (TSC) in a 20 year "traditional" slash-and-burn sequence is (t ha^{-1}): original forest (305) to burned cropland (52) to bush fallow (85) to tree fallow (136) to secondary forest (218). Logging reduced forest system carbon by 124 t ha^{-1}. Ten year-old pastures in Brazil and 13 year-old *Imperata* spp. grasslands in Indonesia contained less TSC than croplands (-4.8 and -5.3 t C ha^{-1}, respectively). Recently established agroforestry systems contained more TSC than did croplands (+13.2 t C ha^{-1}). Mature agroforests (130 t C ha^{-1}) contained significantly greater TSC than croplands, pastures and grasslands but significantly less than secondary forests of similar age. Carbon sequestration rates for natural fallows were 8.4 t C ha^{-1} yr^{-1} following land abandonment. Agroforestry systems, if established at the time of initial land clearing, sequestered 3.3 t C ha^{-1} yr^{-1}.

Pastures/grasslands tended to lose C at a slow rate (240 kg ha^{-1} yr^{-1}). Land-use systems where trees were planted and managed had greater potential to sequester C than did field crops or pastures, but with sequestration rates less than those of natural succession.

1. 1 Above-ground time-averaged carbon stocks

While the global synthesis presented above provides us with information on the trends in C stock changes with differing land-use conversions following slash and burn agriculture, it does not necessarily provide a means of assessing which land-use systems sequester more carbon. To compare the carbon sequestration potential of a land-use system, it is necessary to know the average C stored in that land-use system over the rotation time of that system ($LUSC_{ta}$). In other words, it is not necessarily the maximum C stock of the systems that is important for considering net C fluxes, but rather the average C stock of the system over time.

A forest system has a fairly constant C stock, whereas clearing the forest and establishing tree plantation results in an initial large loss followed by gradual accumulation of C. The plantation may eventually reach 50 to 80% of the C stock of the forest, but the time to accumulate that stock will vary by tree species, management, soils, and climate. The time-averaged C stock depends on the carbon accumulation rates, the maximum C stored in the system, the time it takes to reach maximum C, and the rotation time of the system (Figure 1). The methodology for determining time-averaged C stocks and an example are presented in Appendix 2. The time-averaged carbon stocks, or carbon sequestration potential, were calculated for the above-ground component of the different slash and burn and alternative land-use systems for the three benchmark sites.

Benchmark results

The average maximum carbon stock, regrowth rates, and time-averaged carbon, along with the standard deviation or range in calculations, are summarized by land-use system and benchmark country in Table 1. Detailed worksheets for each country are included in Appendix 3. The results on carbon stock measurements and time-averaged C calculations are presented and discussed based on average values. In addition, Table 1 and Appendix 3 include the standard deviation of the measured stocks and range in calculated time-averaged C to provide an indication of the precision of the estimates.

Brazil The average carbon stock (the above-ground vegetation plus litter) of the 4 selectively logged forests in Brazil was approximately 150 t C ha^{-1}, ranging from 130 to 175. The average value, 150 t C ha^{-1}, was compared to the maximum C sequestered (C_{max}) and time-averaged C ($LUSC_{ta}$) in the following land-use systems (Table 1, Figure 2a):

1) pastures, both traditional and improved;
2) monoculture coffee plantations (1000 plants ha-1), assuming a 7 year establishment phase plus 5 more years of production for a total rotation time of 12 years;
3) multistrata agroforestry systems (includes 3 systems - coffee + rubber, coffee + banderra, cupuacu + pupunha + castanha) with an establishment phase of 12 years and rotation time of 20 years;
4) annual crop-fallow cycles with 3 years of cropping and 5 years of natural fallow;
5) annual crop-improved tree fallow (inga or senna) cycles with 3 years of cropping and 5 years of fallow.

The traditional land-use practice of converting forestlands to pastures results in only 2% of the above-ground C of the forest. The average rotation time of a pasture is 8 to 10 years before re-establishment, but the rotation time, does not have much effect on C storage in pastures because of the constant biomass maintained through grazing. Improving pastures either through management or planting legumes does not increase the carbon storage or time-averaged C stocks above that of the traditional pastures. Lands planted to perennial tree crops attain a maximum C stock of as little as 15 t C ha^{-1} (10% of forest C stock) for monoculture coffee to as much as 90 t C ha^{-1} (54% of forest) for multistrata agroforestry systems of 20 year rotation times. The time-averaged C stocks, however, are only 5 to 26% that of the forest. For land put into an annual crop-fallow rotation, the maximum C stock of a natural fallow of 5 years is 20 t C ha^{-1}, compared to 34 t C ha^{-1} for an improved tree fallow, which is 23% of the forest. The time-averaged C stock of the crop-5 year natural fallow is only 6.86 t C ha^{-1} (5% of the forest). The value increases to only 11.5 t C ha^{-1} for improved tree fallows. The slight increase in C storage and time-averaged C with the improved fallow is due to their high C accumulation rate of 6.86 t C ha^{-1} y^{-1}, compared to 3.91 t C ha^{-1} $y^{-}1$ for the natural fallow. The regrowth rates of the natural fallows are within the range, but at the upper end, of other studies in Brazil (Fearnside and Guimaraes, 1996). The C accumulations rates of the multistrata agroforestry systems were high and similar to the improved fallow.

Cameroon The C stocks (above-ground vegetation and litter) of the 6 selectively logged forests sampled in Cameroon averaged about 228 t C ha^{-1} , ranging from 193 to 252 t C ha^{-1}. This value was compared to data for the following land-use systems (Table 1, Figure 2b).

6) Annual cropping phase of 2 years followed by 4 years of chromolaena fallow,
7) 2 years cropping followed by either 9 or 23 years of bush-tree fallow,
8) 2 years cropping followed by establishment of cacao (jungle cacao) over 25 years,
9) a 40 year rotation versus a non-rotational cacao system established through gap and understorey plantings of cacao,
10) one year cropping followed by establishment of an oil palm plantation with 146 trees ha^{-1} with a 7 year establishment phase and a 25 year rotation.

The maximum C stock attained in the various crop-fallow systems was 167 t C ha^{-1}, for the traditional long fallow. The amount is reduced by more than half, to 76 t C ha^{-1}, if the fallow is shortened to 11 years, and further reduced to 12 t C ha^{-1} with the 4 year chromalaena fallow. The time-averaged C stocks of these crop-fallow rotations are 77, 32, and 5 t C ha^{-1}, respectively. A mature jungle cacao stand contains about 43% of the C of the forest, ranging from 54 to 131 t C ha^{-1}, with an average of 89 t C ha^{-1}. If the jungle cacao system is established simply by clearing the understorey and planting cacao, then the time-averaged carbon of this non-rotational system is the same as the carbon stocks measured. If the system is established through slash-and-burn clearing and cropping followed by planting of cacao with a 25 year establishment phase and total rotation time of 40 years, the time-averaged carbon is 61 t C ha^{-1}. The maximum C and time-averaged C of an oil palm plantation with a 7 year establishment phase and rotation time of 25 years are about half that of the cacao system.

The rates of C accumulation (sequestration rates) varied with age of the fallow; beginning with 2.89 t C ha^{-1} the first two years when chromolaena dominated, increasing to 8.5 t C ha^{-1} for the next 6 to 10 years. The overall accumulation rate during the traditional long shifting cultivation fallows was 7.26 t C ha^{-1}. The C accumulation rate of the rotational jungle cacao was only half that of the natural fallow systems, whereas that of the oil palm plantation was similar at 6.03 t C ha^{-1}. The rates of C accumulation are quite high compared to most reported for the humid tropics but they do fall within the range measured by Szott et al., (1994).

Indonesia The C stocks (above-ground vegetation and litter) of the forests sampled in Indonesia averaged 306 t C ha^{-1} (376 and 236 t C ha^{-1}) for the two primary rainforest sites and 93 t C ha^{-1} (49 to 144 t C ha^{-1}) for the logged-over forests. These forest C stock values were compared to those of the following land-use systems.

11) Annual cropping of 2 years followed by establishment of a rubber plantation (jungle rubber) with a 25 year establishment phase and 30 year rotation time,
12) A non-rotational rubber system established through understorey gap plantings,
13) Establishment of an industrial oil palm plantation with 120 trees ha^{-1} and an establishment phase of 7 years and rotation time of 25 years,
14) Establishment of an industrial timber plantation of fast-growing trees (Paraserianthes, Eucalyptus, Acacia) with a rotation time of 8 years,
15) An annual cropping system of 7 years of cassava followed by 3 years of imperata.

The carbon stock of the logged-over forests in Indonesia is only 24% that of the undisturbed rainforest. Most land conversion in Indonesia follows after logging. The maximum C stock of the jungle rubber system is 89 t C ha^{-1}. The time-averaged carbon for the non-rotational jungle rubber is the same as the average stock (89 t C ha^{-1}), whereas that of the rotational jungle rubber system is only about half, at 46 t C ha^{-1}. The maximum C stored in the monoculture oil palm plantation is about 30% less than that of the rotational jungle rubber (63 t C ha^{-1}), but because of the faster growth and establishment of the oil palm trees, the time-averaged C stock is slightly higher than that of the jungle rubber. The fast-growing timber plantations likewise reach a similar maximum C stock (74 t C) to that of the jungle rubber but in only 8 years as compared to 25 years. The shorter rotation time, 8 years compared to 25 and 30 for the oil palm and jungle rubber, results in a slightly lower time-averaged C. The crop-fallow and cassava-imperata systems have time-averaged C of only 6 and 2 t C ha^{-1}, respectively, less than 2% that of the forest.

The C accumulation rates of the jungle rubber systems in Indonesia (3.6 t C ha^{-1}) were similar to those of the cacao systems in Cameroon. The more intensive plantation systems had much higher C accumulations rates, almost reaching 10 t C ha^{-1} in oil pulpwood plantations.

1. 2 Below-ground carbon stocks and changes

The preceding comparison includes only the above-ground carbon stocks, because the root and soil data were extremely variable. The root data in particular were not useful in making comparisons between land-use systems. Apparently the excavation method used did not adequately sample large roots, so the values for roots in forests and other tree-based systems were underestimates. These data are not included in the report and will not be discussed. The soil data were also variable, partially because of textural differences in the soils of the chronosequence sampled at each site, despite attempts to sample similar soils. Differences in soil C measured in two different land-use systems can in fact be a result of soil textural differences, rather than any effect of land-use. In order to account for the variability caused by differences in soil texture within a site, the soil C data were normalized using the equation developed by van Noordwijk et al., (1997) for estimating the soil C equilibrium values. The equation calculates what the equilibrium soil C would be in a natural, undisturbed system.

Calculated forest soil C = C_{ref} = exp{1.333 + 0.00994*%clay + 0.00699*%silt 0.156*pH_{KCl}}.

The calculated reference values for each site sampled were then compared to the actual C measured (C_{act}), to give a relative C value (C_{rel}) = C_{act}/ C_{ref}. The C_{rel} values obtained for the forest sites were not always predicted by the equation, so the C_{rel} of each land use was divided by the C_{rel} of the forest within each site, to serve as an estimate of the % change in soil C from a particular land-use transition. The relative C values of the different land-use systems compared to that of the forest for each of the benchmark sites are presented in Table 2.

The data in Table 2 indicate that for all the land-use systems considered in Cameroon there is little or no change in soil C. Although these data were not corrected for changes in bulk density, this apparent lack of change is consistent with the relatively low land-use intensity in this benchmark area. Even the cropping systems measured show little change, because they are cropped for only one year prior to abandonment to fallow regrowth. In contrast to Cameroon, in the more intensive pastures and croplands in Brazil and degraded grasslands and continuous cropping in Indonesia, soil C losses of 11 to 53% were found from conversion of forests. This wide range in soil C losses depended on the length of time the land had been in the particular land use, the soil type, and topsoil erosion. In general, the tree-based plantations and agroforestry systems lose less than 20% of the topsoil C, and the complex rubber and cacao agroforests had similar levels of soil C to that of the forests. The relative soil C losses reported for the ASB sites are similar to those reported by Detwiler (1986) in a review of soil C changes with land-use change in the humid tropics.

The CENTURY model has also been used to estimate the equilibrium values of soil C for forest soils (a reference soil C value) in Sumatra and to simulate soil C with different land-use conversions (Sitompul, unpublished data). Overall, the impacts of land-use change on soil C pools as predicted by the CENTURY model agree in magnitude and relation with available soil data from Sumatra. The CENTURY model allows for finer distinctions between various land-use scenarios than does the database (which, for example, lumps all perennial crop plantations into a single category and does not allow for distinctions between oil palm, rubber and *Paraserianthes* plantations, except through their impact on soil pH).

1. 3 Carbon losses and potential for carbon sequestration with alternatives to slash-and-burn agriculture

The time-averaged above-ground C stocks for the different categories of land use across the benchmark sites are summarized in Figure 3 and Table 1. The major conclusions from these data comparisons are:

1. The C stored in the forest systems differed among sites. The highest, >300 t C ha^{-1}, was reported for the undisturbed forests of Indonesia. It is likely that there were no measurements of primary or undisturbed forests at the other sites.
2. The C stocks of the logged forests -- 228, 148, and 93 t C^{-1}ha for Cameroon, Brazil, and Indonesia respectively -- indicate increasing pressure on the forests from farmer-owned logging operations in Cameroon and Brazil to the primarily commercial timber operations

in Indonesia. The logged forests contain only about 50% of the above-ground C of the primary forest, while the soil C stocks do not change significantly.

3. In most places, slash-and-burn clearing is from logged forests, not primary forests. Using the carbon stored in logged forests (93 to 228 t C^{-1} ha) as the point from which other systems are derived, the least intensive traditional crop-long fallow systems still practiced in parts of Cameroon have time-averaged C values of 30% of that of the logged forest.
4. A slight increase in land-use intensity with the jungle rubber or cacao systems of Indonesia and Cameroon results in maximum C stocks of 90 t C ha^{-1} and time-averaged C values of 46 to 61 t C ha^{-1}, 30 to 50% of the logged forest. The time-averaged C stocks of these complex agroforests do not differ much from that of traditional shifting cultivation. The time-averaged C of these systems ranges from 61 t C ha^{-1}, similar to that of the complex agroforests, to 11 t C ha^{-1} for the coffee plantations in Brazil. The simple agroforests include the multistrata systems of Brazil, that contain two to five major tree species, and the monoculture oil palm, pulp wood, and coffee plantations. The more intensively managed tree plantation systems do not necessarily result in time-averaged C values less than the agroforestry systems. Industrial plantations may have lower maximum C stocks, but they reach these levels faster than the agroforests, and, therefore, the time-averaged C values can be as high as the agroforests (Figure 2).
5. The C accumulation rates of the regrowing tree fallow vegetation in Brazil and Cameroon ranged from 3.9 to 8.5 t C ha^{-1} y^{-1}. These rates are considerably higher than the 3.0 to 3.6 t C ha^{-1} y^{-1} found for the complex cacao and rubber agroforests in Indonesia and Cameroon. The industrial timber plantations, oil palm plantations, and simple agroforests, however, had relatively high C accumulation rates, ranging from 6.0 to 9.3 t C ha^{-1} y^{-1}.
6. The soil C stocks in the different land-use systems do not change substantially. Less than 20% of the C in the topsoil (0-20cm) is lost in agroforestry and tree-based systems. The largest drops in soil C (50%) are found in some of the degraded pastures and imperata grassland systems. This 50% drop is equal to a loss of 25 t C ha^{-1}, which is considerably smaller than above-ground losses and potential gains.
7. The potential for C sequestration in the humid tropics is above ground, not in the soil. Table 3 provides a summary of the carbon sequestered or lost from the various land-use conversions. Through the establishment of tree-based systems on degraded pastures, croplands, and grasslands, the time-averaged C stocks in the vegetation increase as much as 50 t C ha^{-1} in 20 to 25 years, while that in the soil will increase by only 5 to 15 t C ha^{-1}.
8. Improved fallow systems do not increase time-averaged carbon sequestration substantially from the currently practiced short fallow systems. This is because of the short duration time of both the improved and natural fallows, resulting in low time-averaged C stocks.
9. Improved pasture management does not show an increase in C stocks above ground or in the topsoil compared to the traditional or degraded pastures, at least to levels that would be significant for C sequestration. Fisher et al., (1994) found substantial amounts of C in the roots and subsoil of improved pastures in savannas in Brazil. Subsoil C was not measured in the ASB plots so there may actually be some storage through improved pastures, although Nepstad et al., (1994) found a dramatic decrease in deep roots on conversion of forest to pasture.
10. The carbon sequestration potential is overestimated by using the maximum C stored in a land-use system (Figure 2). The correct means of calculating and comparing carbon sequestration is by using time-averaged C stored.

1. 4 Data limitations, gaps and recommendations for improving the C stock database

The current dataset allows for general comparison of C stocks and time-averaged C values among general land-use types, but some caution must be taken in using these estimates. There are several steps in which errors may affect the accuracy of the estimates. These include small plot sizes for estimating the biomass of large trees, insufficient numbers of replicates, and inappropriate allometric equations for estimating tree biomass for some of the systems.

The total area sampled for tree biomass at each site was 500 m^2 (= quadrat size (00m^2) multiplied by five (quadrats per site). Although this may be sufficient in areas where trees are small, < 25 cm diameter at breast height (dbh), it is much less than the 2,500 m^2 recommended by Brown et al., (1995) for obtaining accurate measurements in tropical forests where much larger trees are encountered. The protocol has now been modified to increase the quadrat size to 5m X 100m in areas where there are trees with a dbh >25cm.

The above- and below-ground C estimates for most of the land-use systems were obtained from only three or four true field site replicates (in each field site, estimates were obtained from an average of five quadrats = pseudoreplicates). In some cases the variability was quite low, but in others it was unacceptably large, and in other cases the estimates were obtained from only two field site replicates. If these C values are to be used for modeling and national inventories, then the accuracy must be improved by increasing the number of replicates.

Another source of error could be related to the allometric equation used for estimating the biomass of trees based on their diameter. The current equation was developed primarily for mature forests that often included only trees greater than 10 or even 25 cm in diameter (Brown et al., 1989). In addition, the density of the wood in these mature systems may be greater than that in young, regrowing systems. There are indications that this equation may overestimate the C of trees of dbh < 25cm, which, in fact, includes most of the trees in the secondary forests, fallows, agroforestry and tree plantations measured at the ASB sites. New equations being developed based on extensive sampling of trees in young fallows (Ketterings and van Noordwijk for Indonesia and Palm and Szott for Perú) give estimates half those obtained from the Brown equation. Several other recent studies have shown a considerable range in allometric equations for both primary and secondary forests in the humid tropics of Brazil (Alves et al., 1997; Araujo et al., 1999; Nelson et al., 1999).

Application of these new equations to young, regrowing fallow and agroforestry systems will affect carbon stock estimates and rates of C accumulation. Such systems are currently of interest to the global change community as there is debate on how much C is taken up by regrowing vegetation. Once new equations for smaller diameter trees and for specific agroforestry species have been agreed upon, then C stocks, C accumulation rates, and time-averaged C values for many of these systems can be improved relatively rapidly. In addition, since most of the C in these systems is in the trees, we would recommend sampling several more young fallows, mature or growing plantations and agroforestry systems. The tree biomass will be estimated by measuring dbh of the individual trees, noting which species, and then applying the specific allometric equations.

Root sampling and estimation of the C stored in roots has proven to be the most difficult of all the parameters measured. The estimates for roots have not been included in the tables and figures presented in this report. If one assumes that the root-to-shoot ratio remains relatively constant for the different systems within a site, then there is a means of estimating the C stored in the root systems. At the very least, it is possible to say that including roots in the C stock comparisons made above will only magnify the loss of C. As an example, the roots in a plantation will be less than the roots of a forest system, as is the above-ground C, and therefore the difference in total C between the two systems is larger than, but in proportion to, that estimated by above-ground C only.

1. 5 Modeling changes in carbon stocks with changes in land-use

The CENTURY model is a generic plant-soil ecosystem model that can be used to simulate carbon, nitrogen, and phosphorus dynamics of natural and managed ecosystems. Version 4.0 of the model has the ability to simulate complex plant rotations and different types of management practices. The model is well suited for the ASB program because it can simulate the growth of trees and crops and the complex management practices used in the different ASB sites. The various files that have been developed through the collaborative efforts of ASB scientists and the Natural Resource Ecology Laboratory at Colorado State University are listed in Table 4. The site files for the different benchmark sites include the basic soil and climate parameters. The other files are then used to construct the sequence of land-use events (slash-and-burn, crop planting, harvesting, fallow regrowth) that comprise a land-use scenario.

Once tested and validated for the benchmark sites, application of the CENTURY model offers opportunity to explore the productivity and carbon losses and sequestration potential of land-use alternatives beyond the time-frame possible from direct field experimentation, for additional land-use systems and for other soil-climate environments. To date, the model has been set up to simulate the carbon, nitrogen, phosphorus and potassium dynamics for the ASB sites in Indonesia, Cameroon, Brazil, and Perú. The addition of potassium to the CENTURY model was required to simulate crop production on the acid soils of the humid tropics (it could be modified for calcium or other limiting basic nutrients). This addition of potassium was a conceptual advancement for the CENTURY model.

Examples of the simulation modeling and predicting of C stocks for different land-use scenarios can be found in Figures 4 and 5. The first example shows two of the different land-use systems currently being practiced in Indonesia (Figure 4). In both cases the forest is first cleared, as indicated by the dramatic drop in biomass C. In the first case the land is planted to a *Paraserianthes* pulpwood plantation (see Table 1) with an eight-year rotation. In the second case, the land is planted to cassava for five or six years, at which time the field is invaded by Imperata cylindrica; after two or three years in cassava the field is recleared and the cycle starts again.

The simulation matches the total biomass carbon stocks that have been measured in the field for the tree plantation (left hand y-axis) and the cassava/imperata systems (right hand y-axis). The biomass carbon simulated for the primary forest is high by about 25%, indicating there may be a need for further model parameterization and validation for the Indonesia site. The simulated topsoil carbon shows that the tree plantation maintains a steady-state level similar to that of the forest; the blips are a result of the slash that is added and decomposes following tree harvest. Field measurements in the plantation also indicate little or no drop in soil C (Table 2). The cassava/imperata simulation, however, shows a dramatic and continuing decline in soil C, declining by 40% in 20 years – similar to that from field measurements.

The second example from Cameroon simulates the current traditional slash-and-burn agriculture with a declining fallow phase, and two alternative systems. One of the alternatives includes improvements to the current practice, such as soil conservation and retention of some of the larger trees, and the other alternative makes a switch from the current practice to a tree plantation (Figure 5). The total system carbon of the forest and long-term fallow are well-simulated, indicating the model has been fairly well parameterized and validated for the Cameroon site. The alternative system with improved cropping practices shows increases in C stocks compared to that of the traditional system, but the system C still declines, only at a slower rate. If a tree crop plantation is established (in this case a rubber plantation) the maximum C stocks are similar to the slash-and-burn system, and the time-averaged C stock would actually be higher than the traditional system. Additional ASB simulations of various land-use systems have been reported for Indonesia in (Sitompul et al., 1997) and Cameroon (Kotto-Same et al., 1997).

The next step for application of the CENTURY Model to ASB will be require careful comparison of model outputs with results of field studies. A detailed comparison of the model results with the observed data has been run for some of the management practices at the Indonesia and Cameroon sites and needs to be run for all of the sites.

1.6 Relating changes in carbon stocks to changes in land-use cover

Data on carbon stocks and time-averaged C stocks of the different land-use systems can be used to determine past, current, and future scenarios of carbon flux with land-use change over larger areas. Maps of the vegetative land-use cover, based on remote sensing, are available for each of the benchmark areas. In most cases, vegetation cover maps exist for the areas for at least two points in time. The changes in land-use cover found in the areas have been related to the changes in carbon stocks associated with the different land-use conversions, as shown in Table 3. Application of this method to three benchmark areas in Sumatra indicated that Rantau Pandan served as a net sink of –3.1 t C ha-1 yr^{-1} over 64,000 ha for the period 1986 to 1994 (van Noordwijk et al., 1995). This net sink was due to a large area of regrowing jungle rubber. The two other areas, however, served as net sources of emissions: 6.8 t C ha^{-1} yr^{-1} for Muara Tebo (149,000 ha) and 9.0 t C ha^{-1} yr $^{-1}$ for North Lampung (141,000 ha) over the same time period. An example for the entire state of Rondônia, Brazil shows that the conversion of 93,000 hectares of forest to pasture (a change of 170 t C ha^{-1}) over a 20 year period resulted in a net release of 14 million tons of C to the atmosphere (Fujisaka et al., 1998). A similar example for Cameroon, relates the deforestation of 2 million ha from 1973 to 1988 to a release of 200 million ton of C (Kotto-Same et al., 1997).

These estimates are limited by the errors noted before in the estimates for carbon stocks but also by the difficulty in distinguishing among some of the different land-use covers from remote sensing images. Simply detecting forest clearing for cultivation, when the biggest exchange of carbon with the atmosphere occurs, is fairly straightforward. But distinguishing logged forests from primary forests and young fallows from jungle rubber may not be possible, while the differences in the carbon stocks and time-averaged carbon stocks among these land-uses can be fairly large.

GREENHOUSE GAS EMISSIONS FROM SLASH-AND-BURN AND ALTERNATIVE LAND USES AT THE BENCHMARK SITES.

Deforestation and subsequent land use also result in emissions of methane and nitrous oxide, two other greenhouse gases. Methane is the second most important greenhouse gas in terms of amounts and effect in the atmosphere. Most upland, well-drained soils serve as a net sink of methane through consumption of methane by methanotrophic microorganisms in the soil. There is increasing evidence that the size of this sink diminishes with increasing land-use intensity. Conversion to pastures in the humid tropics can actually result in a net source of methane from the soil (Steudler et al., 1996; Keller et al., 1997), through the process of methanogenesis. Factors that affect methane consumption or production in soils include bulk density, water-filled pore space, and nitrogen fertilization. Currently there are insufficient data from the tropics that provide a mechanistic understanding and prediction of the net flux of methane from soils with changes in land use.

Tropical forest soils are also reputed to be a major source of nitrous oxide (Keller et al., 1997). Nitrous oxide emissions can result from the processes of nitrification and denitrification (Firestone and Davidson, 1989) and are affected by N fertilization, land conversion, soil compaction and water logging. Early data from tropical land-use conversion indicated a large flux of nitrous oxide from areas converted to pastures (Luizao et al, 1989). More recent information, however, suggests that this increase in flux is temporary, and the nitrous oxide fluxes may eventually be less than that of the nearby undisturbed forest (Keller and Reiners, 1993; Erickson and Keller, 1997). Nitrogen fertilization seems to be the largest management factor affecting emissions (Davidson, et al., 1996; Erickson and Keller, 1997). Most nitrous oxide measurements in the tropics have been taken from undisturbed forest systems or pastures; few measurements have been taken from areas converted to alternative land uses. A goal of the ASB work during Phase 2 was to sample and compare trace gas fluxes from the natural forests and alternative land uses in the benchmark areas and to identify factors influencing these fluxes.

2.1 Results of rainy season-dry season greenhouse gas monitoring at the benchmark sites.

Progress in measuring gas emissions was severely hampered by the lapse in ASB funding in 1995-6. During that period, however, considerable time and effort were allocated to devise gas sampling, storage and analysis methods that would assure standardization among the sites. The protocol revisions are in accordance with consultations held with experts in the field of trace gas emissions who are associated with the global change research community through the IPCC (International Panel on Climate Change) and GCTE (Global Change in Terrestrial Ecosystems of IGBP) programs. This association of ASB with the global change community is essential if ASB results are to have impact at the larger scale and be incorporated in global change models.

Measurements of CO_2, N_2O, and CH_4 fluxes were made in Brazil, Cameroon, Indonesia, and Perú (work in Perú was funded by ASB-DANIDA) during Phase 2. The measurements were taken in the same locations as those for carbon stocks and biodiversity. Measurements were taken during the rainy season and dry season in Indonesia and Perú but only once, during the rainy season, in Brazil and Cameroon.

The data obtained at the different benchmark areas proved to be extremely variable. In fact, there were no significant differences at any particular site among the different land-use systems, including the natural forests, in terms of nitrous oxide flux or methane consumption. (The data for each of the sites can be found in the ASB country reports). In addition, it is difficult to draw any conclusions from cross-site comparisons, which indicate that the fluxes depended, perhaps, more on soil and climatic conditions of the different sites than on land-use management. For example, N_2O fluxes from the different systems in Perú and Cameroon averaged 57 to 80 ug N m^{-2} hr^{-1}, respectively, and were an order of magnitude higher than the average for Indonesia. Conversely, the methane consumption rates in Indonesia averaged 22 ug C m^{-2} hr^{-1}, almost four times that measured for Perú and Cameroon. The data from Brazil were obtained during an extremely wet period in which the soils were essentially saturated at all sites, and the data were affected by those conditions. There was a net methane flux from most of the system and nitrous oxide fluxes were two orders of magnitude higher than observed in all other sites. We caution that these data should not bias interpretations because of the extraordinary climatic conditions during sampling.

2.2 Results from intensive monthly sampling of greenhouse gas fluxes

Following the first year of monitoring, a conclusion was drawn that reliable estimates or comparisons of gas fluxes cannot be made from only one or two time measurements due to the number and variability of factors affecting the gas fluxes. A decision was made to sample more intensively in a few, well-characterized locations. Two sites, Indonesia and Perú, were chosen for intensive monthly sampling. These sites were selected because of well-defined land-uses and the capacity of the laboratories at the sites to monitor the soil variables that affect gas fluxes. Similar land-use categories are being monitored in the two benchmark areas, representing forests, complex agroforests, fallows, tree plantations, crops, and grasslands. Permanent bases have been established for each chamber so that measurements are taken from the same place each time, reducing the variability and also the disturbance caused by placing the chambers each time. Ancillary soil measurements taken at each sampling time include extractable nitrate and ammonium, N mineralization, nitrification, bulk density, moisture content, texture, pH, and CO_2 evolution.

Though the monthly samplings have not been completed for a year, the data collected for six months in an experiment in Yurimaguas, Perú are presented to show the trends. The experiment compares six different land-use systems. Five of the treatments were established 14 years ago by slashing and burning a 12 year-old forest fallow. Those treatments are 1) shifting cultivation, which entailed one year of cropping and abandonment to forest fallow; the fallow is currently 13 years old; 2) high-input cropping with a maize-soybean rotation and tillage, fertilization, and liming; 3) low-input cropping with an upland rice-cowpea-mucuna rotation; 4) a multistrata agroforestry system; and 5) a peach palm plantation. These treatments are all compared to 6) the original forest fallow that is currently 16 years old. The monthly N_2O fluxes range from 5 to 25 ug N m-2 hr-1 (Figure 6a). Although there are a few months in which there are significant differences among treatments (the high-input cropping treatment is higher following fertilization) the overall mean, 12 ug N m-2 hr-1, for the six months does not indicate any significant differences among the treatments (Figure 6b). These fluxes are 75 to 85% smaller than those measured in Perú in the initial monitoring using removable bases and are similar to those currently being measured in other areas on acid, infertile soils in the humid tropics.

Methane fluxes do, however, show differences among treatments, with the high-input cropping system producing a net efflux of methane to the atmosphere in four of the six months (Figure 7a). Date for the other treatments indicate methane consumption, but the size of this sink decreases with increasing land-use intensity. The largest sink, 25 to 30 ug C m^{-2} hr^{-1}, is found in the two forest fallows and the multistrata agroforestry system, and the smallest, 20 ug C m^{-2} hr^{-1}, is in monoculture peach palm and low-input cropping systems

(Figure 7b). These differences in CH_4 flux are related primarily to increased bulk density and resulting water-filled pore space in the cropping systems and peach palm plantation. These methane consumption rates are similar to those reported from the first year of monitoring in Indonesia.

Data obtained from the monthly measurements in Perú and Indonesia will be used to test a gas flux model for the tropics. A new version of the CENTURY model (NGAS-CENTURY) has been developed to simulate trace gas production. The NGAS-CENTURY version uses a daily time step and can simulate daily CH_4 consumption, and N_2O, NO_x and N_2 gas fluxes. Once NGAS-CENTURY has been validated and tested for the benchmark sites, it can then be used to predict trace gas fluxes from a variety of environments and land management systems that cannot possible be accomplished through intensive field sampling due to the expense and time involved.

2.3 Net radiative forcing of greenhouse gas emissions from slash-and-burn and alternative land-use systems

The net effect, or net radiative forcing of the fluxes of the different greenhouse gas, CO_2, N_2O, and CH_4, or the relative contribution of the individual gases can be compared based on the global warming potential (GWP) of the different gases. Various conversions factor are used for GWP; an example from Lal et al., (1998) is that the GWP is 1 for CO_2, 21 for CH_4 and 310 for N_2O. In other words, an equivalent weight of nitrous oxide has a much stronger effect on radiative forcing than the same weight of carbon dioxide or methane. Based on the GWP of the different gases, a calculation from preliminary data in Indonesia compared the overall effect of release of CO_2 from deforestation and the resorption of C from the vegetation of the replacement land-use system (based on the time-averaged C) and the release of N_2O and sink of CH_4 over a 25-year time course (Tomich et al., 1998). They found that the initial loss of CO_2 through deforestation is by far the largest factor in terms of net radiative forcing. This may be different in intensive systems where N fertilizers are applied; we do not yet have estimates from such systems in ASB, but other studies (Davidson, et al., 1996; Erickson and Keller, 1997) would indicate this to be the case.

ASSESSMENT OF LAND-REHABILITATION TECHNIQUES FOR INCREASING CARBON SEQUESTRATION

Various options for increasing the agricultural productivity at the ASB benchmark sites also have the potential to increase carbon sequestration. As mentioned in section 1.3, if degraded lands are planted to tree-based systems, the time-averaged C stocks in the vegetation increase as much as 50 t C ha^{-1} in 20 to 25 years, while that in the soil increases by only 5 to 15 t C ha^{1}. Table 3 indicates the amount of above-ground carbon that could be sequestered through rehabilitation of degraded lands by conversion to other land-use systems. Extensive areas of degraded pastures in Brazil and degraded imperata grasslands in Indonesia could benefit from such rehabilitation. Efforts of teams in both countries are currently addressing this issue. It not just technological information that is necessary for rehabilitation of these degraded lands. Often it is policy issues, including land tenure and tree rights, as well as access to and the costs of inputs needed to implement the rehabilitation strategies, which prevent them from succeeding. This topic will be a major focus of the next phase of ASB.

THE NEXT PHASE OF CARBON STOCK AND GREENHOUSE GAS EMISSION RESEARCH FOR ASB

The following set of hypotheses were developed based on the results from the different benchmark sites in the first two phases of ASB. These hypotheses will guide the next phase of research in order to increase our ability to estimate and predict the effects of land-use change in the tropics on climate change.

C sequestration

- Carbon accumulation rates of natural fallow systems are higher than those of agroforestry systems.
- Time-averaged carbon stocks of tree-based systems are determined primarily by rotation length and tree planting or regeneration strategy and not by species diversity.
- Changes in above-ground C stocks have a greater effect on net radiative forcing impact than do changes in below-ground C stocks, N_2O emissions and CH_4 sink strength.

Nitrous oxide emissions

- N_2O fluxes are linked primarily to anaerobic conditions and are thus more related to the soil type, primarily texture, and landscape position, than to land use *per se* (unless N fertilizers are applied).
- On a given soil type and landscape position, N_2O emissions are directly related to above-ground carbon and nitrogen stocks (and cycling), unless nitrogenous fertilizers are applied.
- Given equal above-ground carbon stocks, N_2O fluxes are not affected by plant biodiversity.

Methane sinks

- CH_4 fluxes are more related to soil type, landscape position, and water balance than to above-ground vegetation of the land use (unless N fertilizers are applied).
- Changes in CH_4 sink strength are directly related to changes in bulk density and surplus soil N, as a result of land-use change.
- At equal above-ground C stocks, CH_4 fluxes are not affected by above-ground biodiversity.

These hypotheses will be addressed through selective sampling in locations that will allow such comparisons to be made. The teams at the benchmark sites are already trained in the various protocols for measuring C stocks and greenhouse gas emissions and modeling C changes with CENTURY. The capacity building will continue, but the investment during the first two phases of ASB provide the human capital needed to undertake this next phase.

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ACKNOWLEDGEMENTS

The work reported here was made possible through grants from the Global Environment Facility (GEF) and DANIDA. In addition, each of the collaborating institutions contributed substantially in terms of staff, facilities, operations, and enthusiasm far beyond usual counterpart contributions.

Table 1: **Summary of the land-use systems sampled at the ASB sites, including average C stocks (standard deviation) and age of the systems sampled, the C accumulation rates, maximum C stock, and land-use system time-averaged C stock**

Land-use Systems	**Country and Specific Land-use**		**Reps**	**AverageC stock (stdv)**	**Age (stdv)**	**C accumulation rate, 1c** *$t\ C\ ha^{-1}\ y^{-1}$* **(stdv)**	**Age at maximum C**	**Maximum C stored*** *$t\ C\ ha^{-1}$*	**Time-averaged C of Land-use System** LUSCta** *$t\ C\ ha^{-1}$*
Undisturbed Forest	Indonesia		2	306 (99)	?	NA	NA	306 (207 - 405)	306 (207 - 405)
Logged Forests	Brazil		4	148 (19)	?	NA	NA	148 (129 - 149)	148 (129 - 149)
	Cameroon		5	228 (27)	?	NA	NA	228 (221- 255)	228 (221- 255)
	Indonesia		4	93.2 (41.3)	?	NA	NA	93.2 (51.9 –134.5)	93.2 (51.9 –134.5)
Shifting Cultivation and crop-fallows	Cameroon	Shifting cultivation, 23 year fallow	7	131 (37)	18.5 (4.2)	7.26 (2.02)	23	167 (120 – 213)	77.0 (60.2 – 107)
		Bush fallow, 9 yrs	6	64.1(18.8)	76	8.46(2.22)	9	76.1 (56.2 – 96.3)	602-107
		Chromolaena fallow	6	5.78 (2.76)	2	2.89 (1.38)	4	11.6 (6.04-17.08)	4.52 (2.68 – 6.38)
	Brazil	Short fallow	3	15.4 (9.43)	4	3.91 (1.66)	5	19.6 (1.2-28.4)	6.86 (4.27-9.61)
		Improved fallow		13.7 (2.51)	2	6.86 (1.26)	5	28.0-40.6)	11.5 (9.50-13.4)
Complex Agroforests	Cameroon	Cacao	5	88.7 (31.6)	NA	NA	NA	88.7 (57.2-120)	88.7 (57.2-120)
Permanent	Indonesia	Rubber	4	89.2 (39.8)	NA	NA	NA	89.2 (49.4 - 129)	89.2 (49.4 - 129)
Complex Agroforests	Cameroon	Cacao	5	88.7 (31.6)	25 (0)	3.55 (1.26)	25	88.7 (57.2-120)	61(40-83)
Rotational	Indonesia	Rubber	4	89.2 (39.8)	30	3.57 (1.59)	25	89.2 (49.4 - 129)	46.2 (28.9-75.2)
Simple Agroforestry	Brazil	Coffee monoculture	3	15.0 (2.66)	8 (2.31)	2.14 (0.38)	7	15.0	11.0 (8.73-12.5)
		Multistrata system	3	70.5 (24.3)	10	7.26 (1.63)	12	87.1 (67.6-106.7)	61.2 (47.5-74.7)
	Cameroon	Oil Palm	1	42.2	15	6.03	7	42.2	36.4
	Indonesia	Pulp trees	2	22.0 (1.91)	2.5	9.29 (3.39)	8	74.3 (47.2-101)	37.2 (23.6-50.7)
Pastures and Grasslands	Brazil	Traditional pastures	4	5.70 (3.43)	11	-	-	-	2.85
		Improved pastures	3	6.04 (1.91)	11	-	-	-	3.06
	Indonesia	Cassava/Imperata	11	2.05 (0.98)	-	-	-	1.97	<2

**the range is given in parentheses and is determined by multiplying the age at maximum C by +/- 1 standard deviation of the C accumulation rate

** the range was obtained as above, for details see Appendix 3

Table 2. **Soil carbon values corrected according to the equation of van Noordwijk et al., (1997) and compared to the forest system for each land-use system in the benchmark sites.**

Land-use Country	C actual	C reference	C relative	C_{rel} Land-use/ C_{rel} Forest
BRAZIL				
Forest	1.78	3.35	0.53	1.0
Agroforestry	1.52	3.51	0.43	0.81
Fallows	0.96	2.80	0.35	0.65
Pasture	1.12	2.84	0.41	0.77
Crop	1.70	3.58	0.48	0.89
CAMEROON				
Forest	1.56	2.97	0.53	1.0
Jungle Cacao	1.47	2.62	0.57	1.09
Chromolaena fallow (8yrs)	1.72	3.04	0.57	1.08
Chromolaena fallow (2yrs)	1.49	4.22	0.53	1.01
Crop	1.62	2.81	0.58	1.10
INDONESIA				
Forest	NA	NA	1.23	1.0
Logged Forest	.	.	1.35	1.09
Jungle rubber	.	.	1.38	1.12
Pulpwood plantation	.	.	1.23	0.99
Rubber plantation	.	.	0.99	0.80
Cassava	.	.	0.81	0.66
Imperata	.	.	0.58	0.47

NA - data not available

Table 3. Carbon sequestered (- t C ha-1) or lost (+) from converting from one land-use system to another1

INDONESIA	**Primary forest**	**Logged Forest**	**Jungle Rubber** (permanent)	**Jungle Rubber** (rotational)	**Oil Palm**	**Pulp Plantation**	**Crop/imperata**
Time-averaged C (t C ha^{-1})	306	93	89	46	54	37	2
	Carbon sequestered (-) or lost (+) during land-use transition from row to column						
Logged Forest	213	NA	-4	-47	-39	-56	-91
Jungle Rubber (permanent)	217	4	NA	-43	-35	-52	-87
Jungle Rubber (rotation)	260	47	-43	NA	8	-9	-44
Oil Palm	252	39	-35	-8	NA	-17	-52
Pulp Plantation	269	56	-52	9	17	NA	-35
Crop/imperata	304	91	-87	44	52	35	NA

CAMEROON	**Logged Forest**	**Shifting cultivation**	**Jungle Cacao**	**Oil Palm**	**Crop/ bush fallow**	**Crop/ Chromolaena**
Time-averaged C (t C ha^{-1})	228	77	61	36	38	6
	Carbon sequestered (-) or lost (+) during land-use transition from row to column					
Forest	NA	-151	-167	-192	-190	-222
Shifting cultivation	151	NA	-16	-41	-39	-71
Jungle Cacao	167	16	NA	-25	-23	-55
Oil Palm	192	41	25	NA	2	-30
Crop/Bush fallow	190	39	23	-2	NA	-32
Crop/Chromolaena	222	71	55	30	32	NA

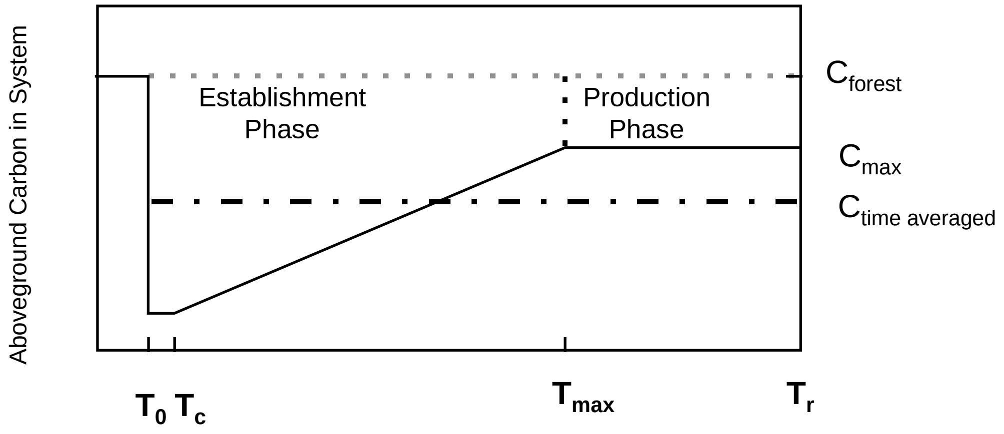
BRAZIL	**Logged Forest**	**Multistrata Agroforesty**	**Coffee Plantation**	**Crop/ Improved fallow**	**Crop/ Fallow**	**Pasture**
Time-averaged C (t C ha^{-1})	148	61	11	11	7	3
	Carbon sequestered (-) or lost (+) during land-use transition from row to column					
Forest	NA	-87	-137	-137	-141	-145
Multistrata AF	87	NA	-50	-50	-54	-58
Coffee	137	50	NA	0	-4	-8
Crop/improved fallow	137	50	0	NA	-4	-4
Crop/fallow	141	54	0	NA	NA	-8
Pasture	145	58	8	8	4	NA

[1] The amount of carbon reflects the loss or gain in switching from the land use in the row heading to that in the column heading.

Table 4. CENTURY files for use in simulations of various ASB land-use systems for the benchmark sites.

Site files	**Tree files**
Jambi/Lampung, Indonesia	Tropical – general
Ebolowa, Cameroon	Oil palm
M’balmayo, Cameroon	Peach palm
Theobroma, Brazil	Rubber
Yurimaguas, Perú	Paraserianthes
	Coffee
Crop files	**Tree harvest and burn files**
Groundnut	Products – fruits, oil, branches
Cowpea	Logging
Maize	Selective
Upland rice	Clear cut
Cassava	Slash and burn
Banana	% of trees cut
Grass	Intensity of burn
Imperata	
Other files	
Fertilization, Irrigation, Tillage, Grazing, Crop harvest, Organic additions	

Figure 1a. Schematic of above-ground C losses and reaccumulation following forest clearing and cropping and fallow re-establishment.



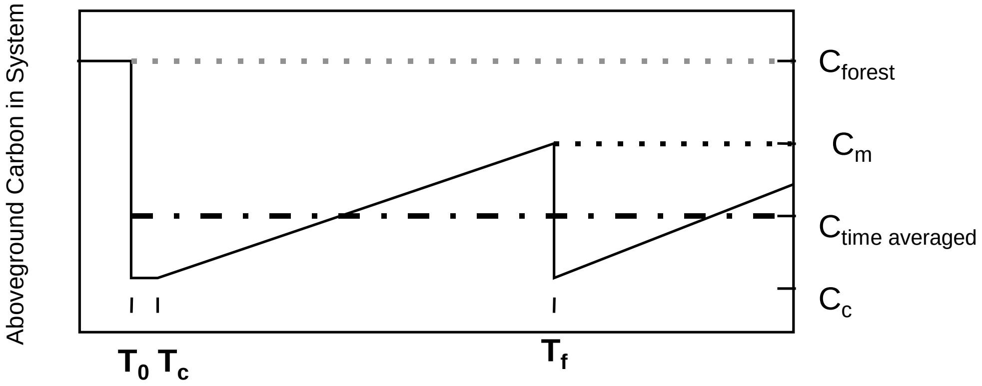
Maximum C in system = $C_{max} = I_c * T_{max}$

Time averaged C in system = $LUSC_{ta}$
= Weighted mean (C_{ta} Establishment and Production Phases)

C_{ta} Establishment Phase = $C_{estab} = (I_c * T_{max})/2$
C_{ta} Production Phase = $C_{prod} = C_{max}$

= $[(C_{estab} * T_{max}) + (C_{prod} *(T_r-T_{max})]/ T_r$

Figure 1b. Schematic of above-ground C losses and reaccumulation after forest clearing and establishment of a tree plantation.



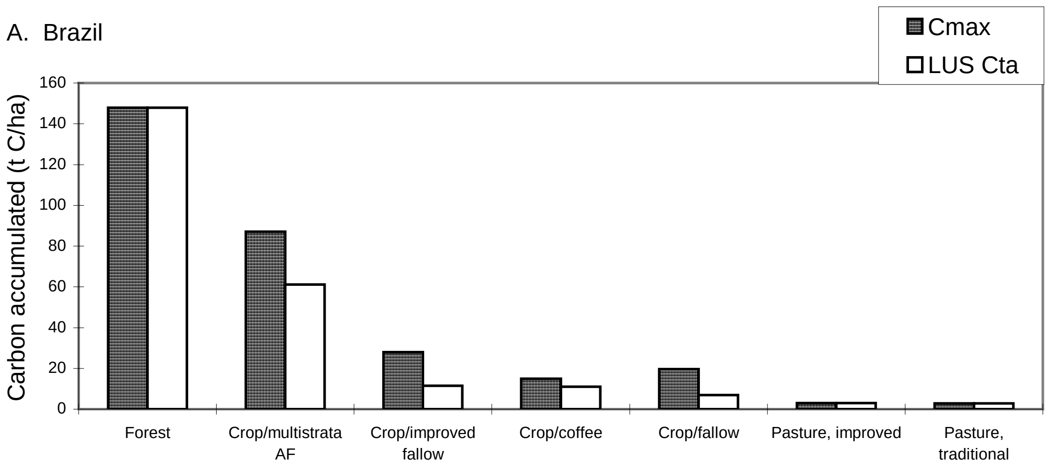
C accumulation rate = $I_c = (C_m - C_c)/(T_f - T_c)$, or if T_c and C_c are small then,
$I_c = C_m/T_f$.

Time averaged C = $(I_c * T_f)/2$, assuming T_c and C_c are small.

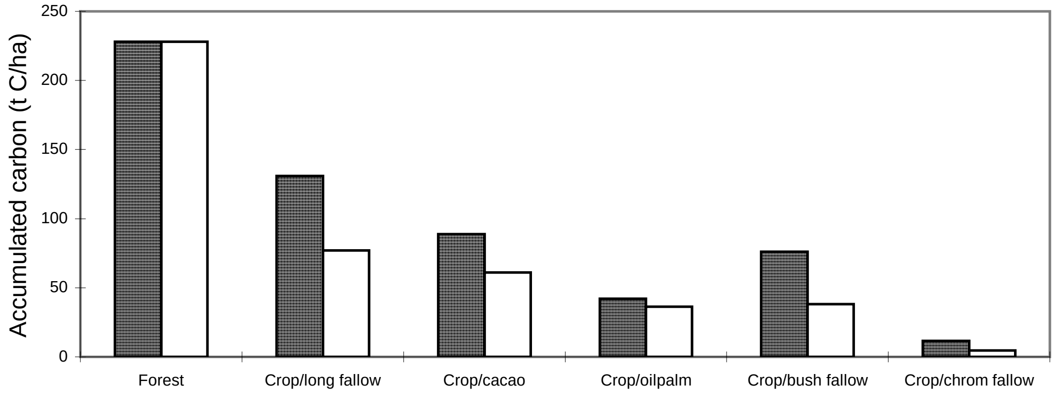
C_m= carbon in fallow at time of clearing
C_c= carbon in crop, assumed to be negligible
C_{ta} = Time averaged carbon
T_f = Time (years) in fallow phase
T_c = Time in crop phase, assumed short compared to $_f$.

Figure 2. Maximum C stock (Cmax) and land use time-averaged C (LUSCta) for the different ASB land use systems.

A. Brazil



B. Cameroon



C. Indonesia

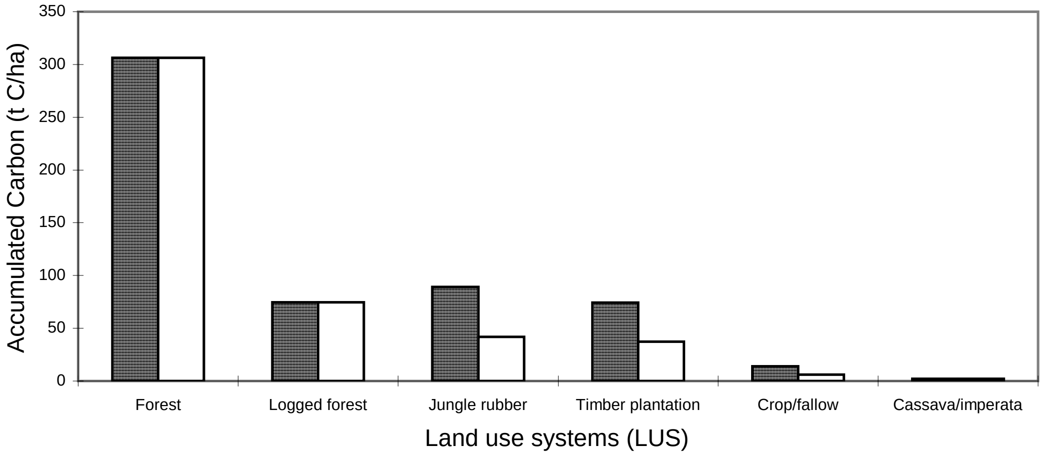


Figure 3. Above-ground time-averaged and total soil carbon (0-20 cm) for all benchmark sites

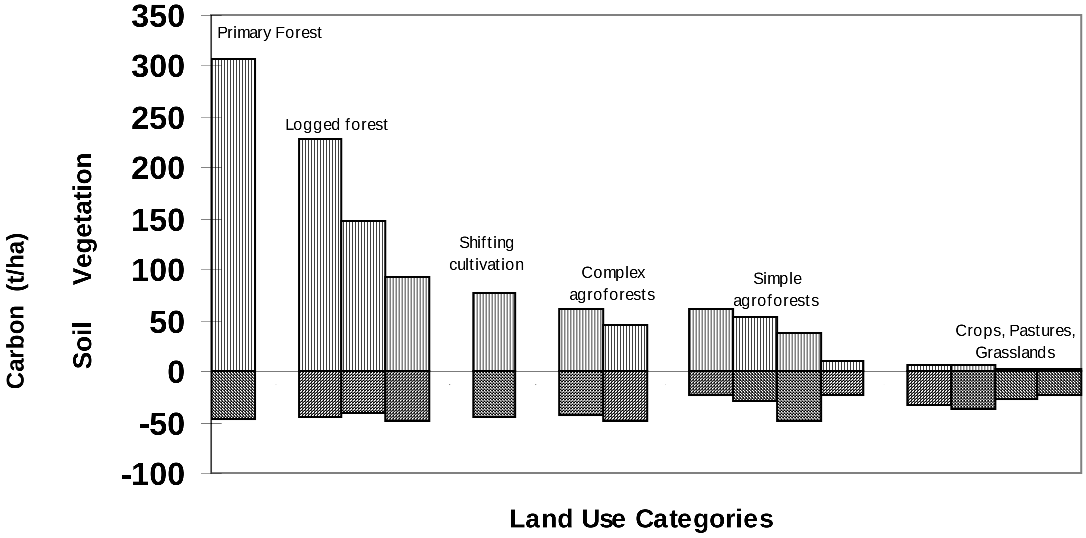


Figure 4. **CENTURY simulation of the biomass C and top soil C changes on conversion of forest to 1) *Parasarionthes* plantation and 2) *Cassava/imperata* rotation (Indonesia case)**

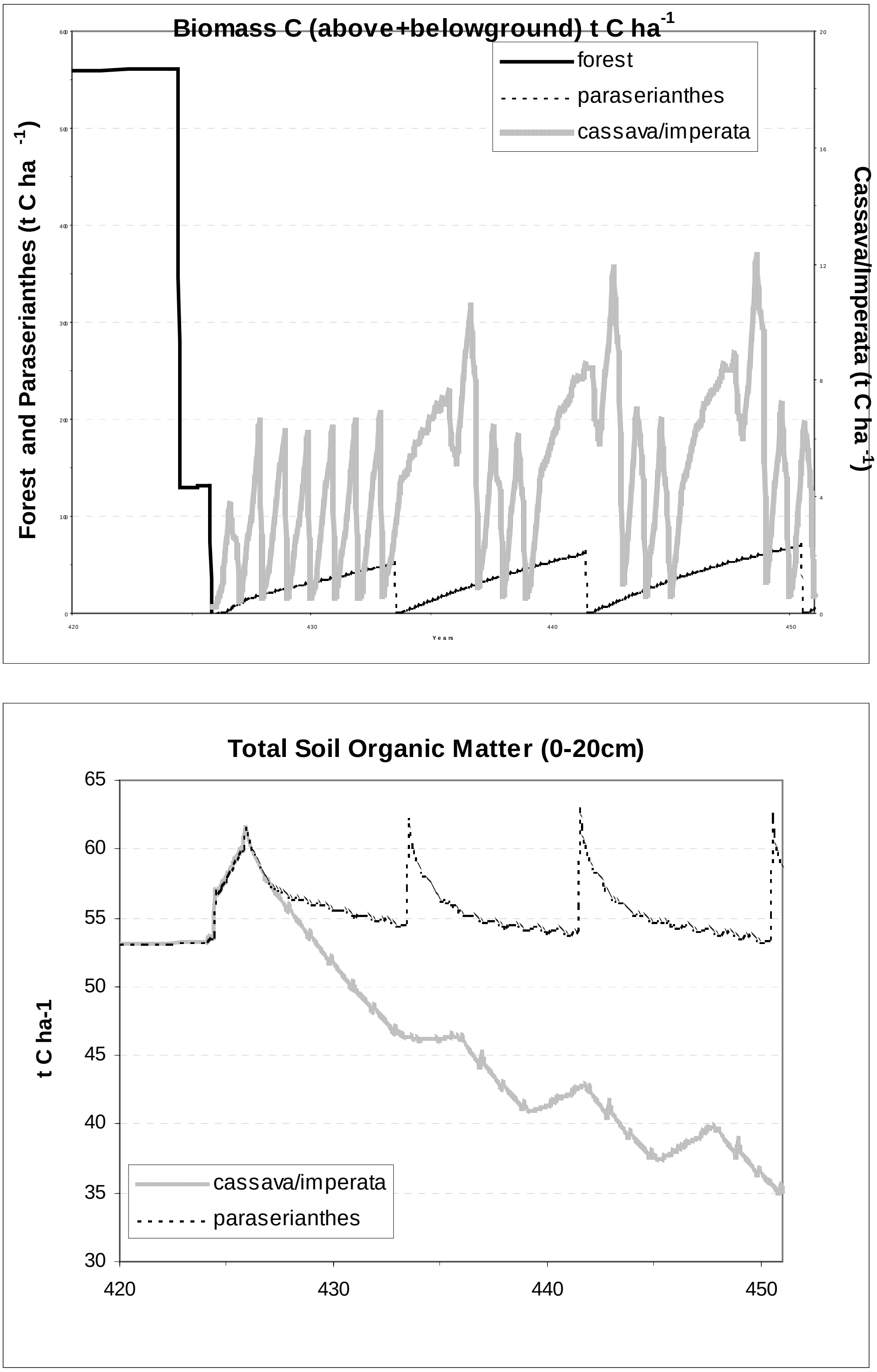
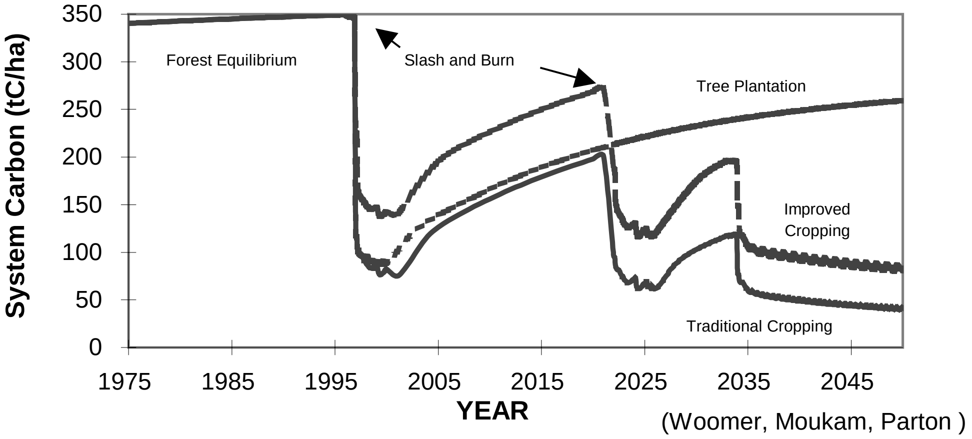
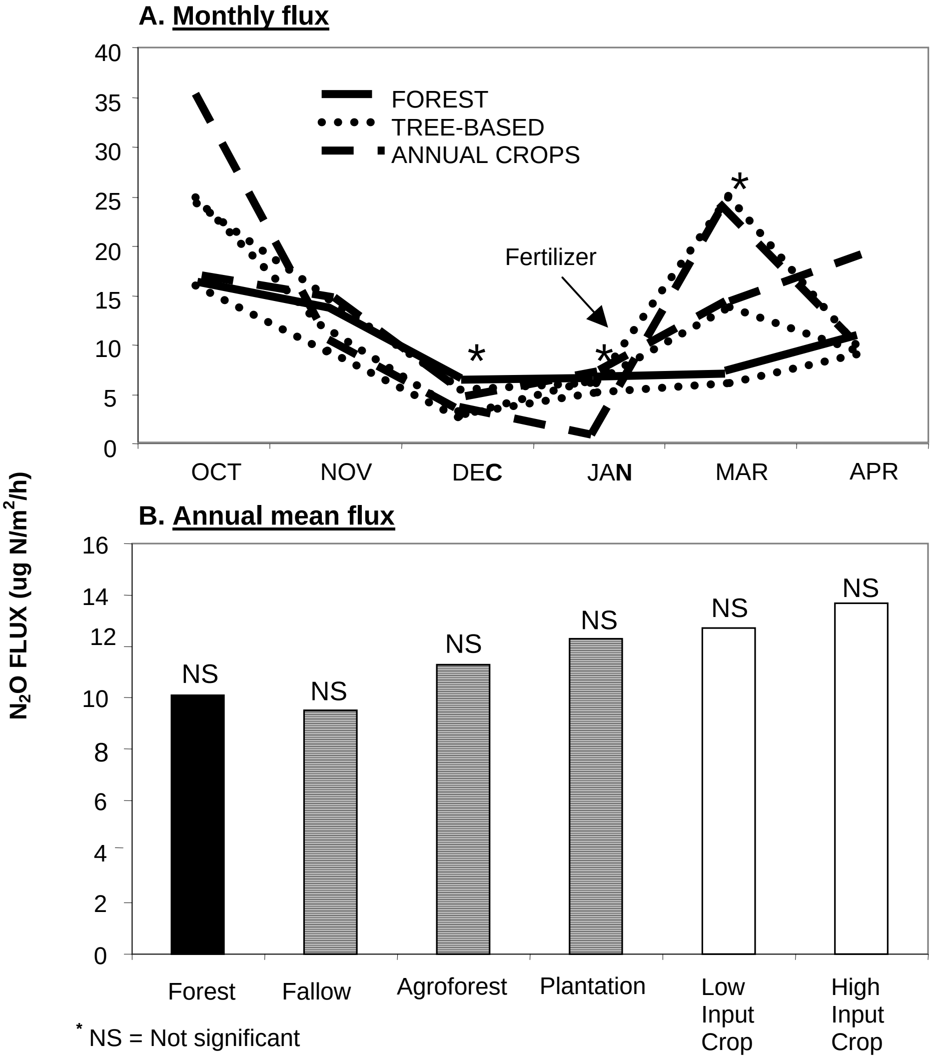


Figure 5. CENTURY Model simulations of changes in carbon stocks with slash and burn and alternative land uses (Cameroon Case).



(Woomer, Moukam, Parton)

Figure 6. Nitrous oxide fluxes from 6 land use systems in Yurimaguas, Peru

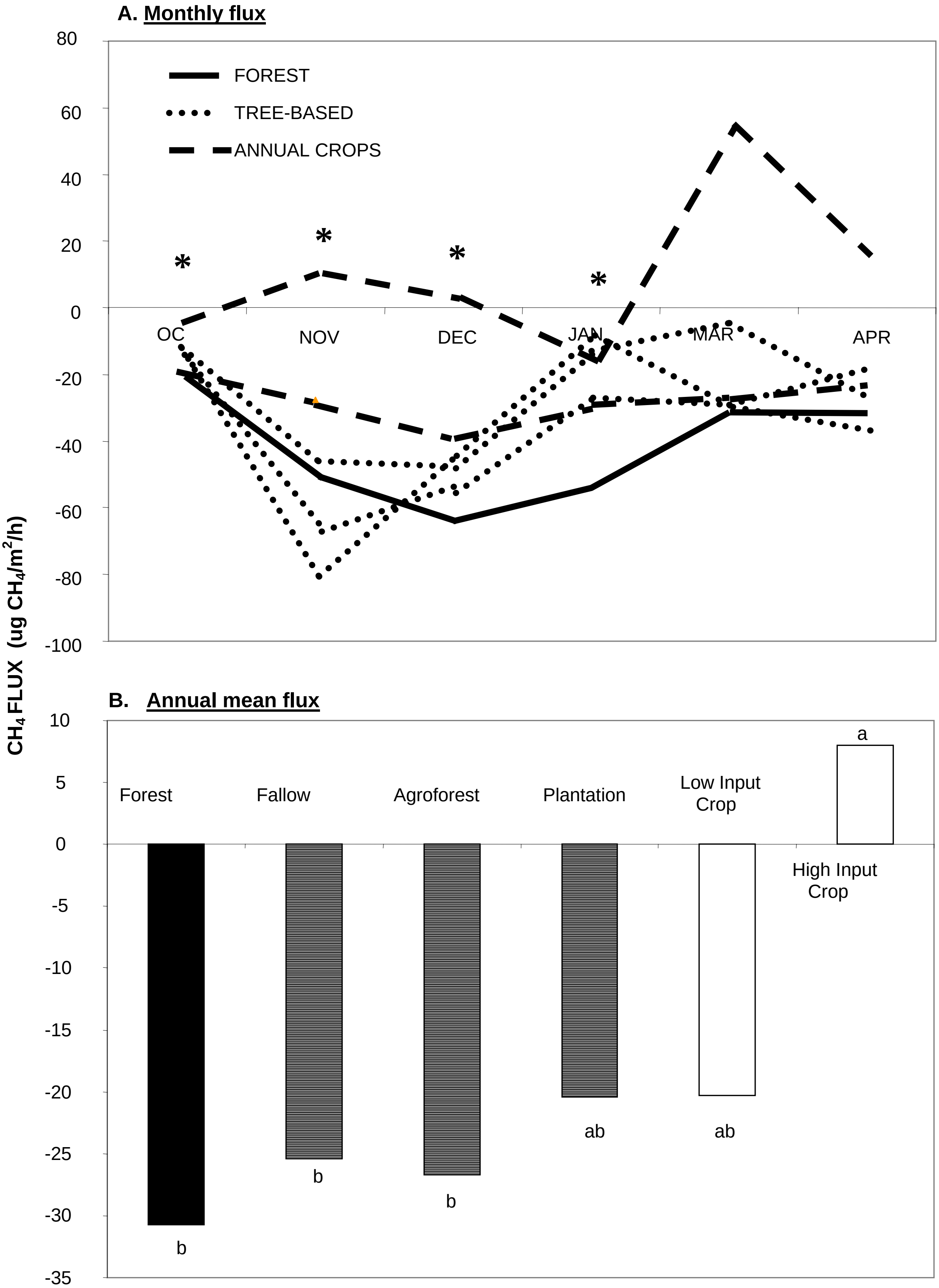


A. Monthly flux

B. Annual mean flux

* NS = Not significant

Figure 7. Methane fluxes from 6 land use systems in Yurimaguas, Peru



*Different letters indicate statistical significance.

APPENDICES

Appendix 1: Carbon stock (t ha^{-1}) dataset for the ASB benchmark sites.

(ASB site# refers to co-located biodiversity plot numbers)

ASB Site#	Carbon case#	Country	Bench mark	long	lat	Land-use System	Specific use	Age since burn	abvgrndC	soil C (0-20)*
	73	bra	ppeix	.	.	past	pasture+pueraria	6	7.04	21.17
	76	bra	ppeix	.	.	past	Brizatha+pueraria	11	7.25	34.21
BRA20	77	bra	ppeix	67.09	10.01	past	pasture	11	6.26	44.85
BRA018	75	bra	ppeix	67.09	10.01	newfal	natural fallow	3	17.33	40.64
BRA014	71	bra	ppeix	.	.	newaf	Ppalm/cup/bnut	6	49.79	35.00
	72	bra	ppeix	.	.	newaf	ppalm/heart	6	36.36	24.93
BRA017	69	bra	ppeix	67.09	10.01	lfor	logged forest	NA	142.05	33.07
	70	bra	ppeix	.	.	lfor	logged forest	NA	131.88	30.37
	74	bra	ppeix			midfal	natural fallow	10	23.70	29.13
	78	bra	ppeix	.	.	imp	imperata	11	2.06	24.53
	83	bra	theo	62.11	10.06	past	trad pasture	12	5.82	.
	87	bra	theo	62.23	10.13	past	trad pasture	11	9.51	.
	97	bra	theo	.	.	past	improved pasture	13	3.84	26.37
	98	bra	theo	.	.	past	degraded pasture	13	1.19	26.78
	88	bra	theo	.	.	oldaf	coffee mono	15	16.59	16.37
BRA001	89	bra	theo	61.57	10.55	oldaf	coffee + rubber	15	97.19	12.72
BRA005	90	bra	theo	62.00	10.58	oldaf	coffee + timber	15	64.50	23.33
	81	bra	theo	62.11	10.06	newfal	natural fallow	5	62.74	.
	85	bra	theo	62.23	10.13	newfal	natural fallow	5	121.27	.
BRA008	91	bra	theo	62.11	10.06	impfal	imp fallow inga	5	13.85	41.54
BRA009	92	bra	theo	62.11	10.06	impfal	imp fallow senna	5	11.84	36.76
	93	bra	theo	62.11	10.06	impfal	imp fallow inga	5	17.23	44.54
	94	bra	theo	62.11	10.06	impfal	imp fallow senna	5	11.97	31.77
	95	bra	theo	62.11	10.06	impfal	imp fallow pueraria	5	3.06	36.80
	96	bra	theo	62.11	10.06	newfal	natural	4	5.15	39.42
BRA010	82	bra	theo	62.11	10.06	newaf	coffee	11	16.38	.
	86	bra	theo	62.23	10.13	newaf	coffee	11	11.89	.
	79	bra	theo	62.11	10.06	lfor	logged forest	NA	142.70	.
BRA012	84	bra	theo	62.23	10.13	lfor	logged forest	NA	175.20	.
	80	bra	theo	62.11	10.06	crop	crop	1	35.98	.
	33	cam	ebol	11.25	2.42	oldfal	natural fallow	22	208.43	51.20
	38	cam	ebol	11.03	2.59	oldfal	natural fallow	20	104.64	48.13
	32	cam	ebol	11.25	2.42	lfor	logged forest	NA	248.28	57.40
CAMASB08	37	cam	ebol	11.03	2.59	lfor	logged forest	NA	205.35	45.51
	34	cam	ebol	11.25	2.42	oldaf	Jcacao	25	131.64	49.60
CAMASB10	39	cam	ebol	11.03	2.59	oldaf	Jcacao	25	100.14	41.80
	36	cam	ebol	11.25	2.42	newfal	natural fallow	4	7.19	51.70
CAMASB09	41	cam	ebol	11.03	2.59	newfal	natural fallow	4	6.10	29.95
	35	cam	ebol	11.25	2.42	midfal	natural fallow	10	36.35	54.60
	40	cam	ebol	11.03	2.59	midfal	natural fallow	11	89.23	39.61
	42	cam	ebol	11.03	2.59	crop		1	0.00	55.66
	46	cam	mbal	11.61	3.61	oldfal	natural fallow	15	141.12	60.80
	52	cam	mbal	11.79	3.30	oldfal	natural fallow	15	98.70	36.40
CAMASB01	45	cam	mbal	11.61	3.61	lfor	logged forest	NA	252.02	49.40
	51	cam	mbal	11.79	3.30	lfor	logged forest	NA	192.60	37.40
	48	cam	mbal	11.61	3.61	oldaf	Jcacao	25	54.23	52.80
	54	cam	mbal	11.79	3.30	oldaf	Jcacao	25	61.00	32.50
CAMASB02	49	cam	mbal	11.61	3.61	newfal	natural fallow	4	10.40	58.20
	55	cam	mbal	11.79	3.30	newfal	natural fallow	4	4.30	31.20
CAMASB04	47	cam	mbal	11.61	3.61	midfal	natural fallow	9	67.15	40.30

	53	cam	mbal	11.79	3.30	midfal	natural fallow	9	65.90	35.90
CAMASB03	50	cam	mbal	11.61	3.61	crop		1	0.00	41.30
	56	cam	mbal	11.79	3.30	crop		1	0.00	17.90
	58	cam	yao	11.26	4.24	oldfal	natural fallow	20	107.90	32.20
	64	cam	yao	11.57	3.93	oldfal	natural fallow	15	126.70	45.00
	57	cam	yao	11.26	4.24	oldfal	natural fallow	25	129.00	33.00
	63	cam	yao	11.57	3.93	lfor	logged forest	NA	239.60	37.50
	60	cam	yao	11.26	4.24	oldaf	Jcacao	25	96.60	39.50
	61	cam	yao	11.26	4.24	newfal	natural fallow	4	2.80	20.50
CAMASB06	67	cam	yao	11.57	3.93	newfal	natural fallow	4	3.90	42.50
	59	cam	yao	11.26	4.24	midfal	natural fallow	9	114.40	36.90
	65	cam	yao	11.57	3.93	midfal	natural fallow	9	61.80	30.00
	62	cam	yao	11.26	4.24	crop		1	2.00	22.90
CAMASB07	68	cam	yao	11.57	3.93	crop		1	2.00	37.50
ASBJAM1	17	ind	jam	102.10	1.07	oldf	forest	NA	376.31	56.43
ASBJAM2	18	ind	jam	102.10	1.08	lfor	logged forest	NA	105.51	48.51
ASBJAM4	19	ind	jam	101.93	1.67	oldf	forest	NA	236.20	34.97
ASBJAM5	20	ind	jam	101.94	1.66	oldaf	Jrubber	30	41.55	70.20
ASBJAM6	21	ind	jam	102.27	1.59	oldaf	Jrubber	30	95.96	28.95
	22	ind	jam	102.27	1.58	oldaf		30	60.08	27.36
ASBJAM15	23	ind	jam	102.37	1.53	oldaf	Jrubber	30	81.31	49.37
ASBJAM3	24	ind	jam	102.11	1.08	newaf	paraserianthes	5	20.67	37.87
ASBJAM11	25	ind	jam	102.39	1.55	newaf		5	6.29	60.32
	26	ind	jam	102.42	1.55	newaf		5	21.02	38.99
ASBJAM9	29	ind	jam	102.35	1.59	imp	imperata	22	1.80	48.44
ASBJAM10	30	ind	jam	102.35	1.59	imp	imperata	22	2.49	39.76
ASBJAM8	27	ind	jam	102.30	1.59	crop	cassava	3	2.22	30.10
ASBJAM14	28	ind	jam	102.34	1.60	crop	cassava	3	1.41	22.87
ASBLAM01	1	ind	lam	104.92	4.50	lfor	logged forest	NA	144.62	54.72
ASBLAM05	2	ind	lam	104.98	4.43	lfor	logged forest	NA	49.07	48.26
ASBLAM14	3	ind	lam	105.04	4.47	lfor	logged forest	NA	73.61	45.75
ASBLAM09	4	ind	lam	105.04	4.48	oldaf	fruit agroforest	30	94.33	31.39
ASBLAM12	5	ind	lam	105.02	4.46	oldaf	fruit	30	77.99	80.43
ASBLAM15	6	ind	lam	105.06	4.47	oldaf	rubber+banan	30	137.80	42.60
ASBLAM04	7	ind	lam	104.92	4.45	newaf	oilpalm	8	65.14	29.08
ASBLAM06	8	ind	lam	104.98	4.43	newaf	paraserianthes	2	23.38	57.54
ASBLAM13	9	ind	lam	105.05	4.47	newaf	rubber+banana	3	9.22	31.37
ASBLAM03	13	ind	lam	104.92	4.46	imp	imperata	9	3.51	35.78
ASBLAM08	14	ind	lam	104.99	4.44	imp	imperata	9	2.92	40.29
ASBLAM11	15	ind	lam	105.03	4.46	imp	imperata	9	1.01	19.20
ASBLAM16	16	ind	lam	105.01	4.45	imp	imperata	9	1.50	37.39
ASBLAM02	10	ind	lam	159.26	4.45	crop	cassava	3	3.60	28.02
ASBLAM07	11	ind	lam	105.01	4.45	crop	cassava	3	1.39	15.90
ASBLAM10	12	ind	lam	105.04	4.47	crop	cassava	3	0.74	21.76

Appendix 2. Method for calculating time-averaged carbon stocks of a land-use system.

Time-averaged carbon for the different land-use systems at the ASB sites was calculated as follows: 1) calculation of the C accumulation rates (^{Ic}) for each land-use system based on the carbon stock and the average age of each system sampled, and 2) calculation of time-averaged C stocks for the duration (rotation time) of each land-use system based on the C accumulation rates and duration of each of the phases in that particular land-use system.

Carbon accumulation rates (I_{c}, t C ha^{-1} yr^{-1}) for fallow regrowth were determined according to the method described by van Noordwijk (ICRAF, 1996) where the average C stock value of the fallows sampled (C_s) was divided by the average age (T_s) of the plots sampled (Figure 2). It is assumed that the carbon increase rates (I_c) are linear throughout the time period of fallow regrowth (T_f). The carbon stored in fallows (C_m) of specific ages (T_f) can then be determined as: $C_m = I_c * T_f$. The time-averaged C stock for a crop-fallow system that has little time in the cropping phase and negligible C stored over that time is essentially the C stored in the fallow vegetation at the time of reclearing (C_m) divided by 2 or the C accumulation rate (I_c) time the number of years of fallow (T_r) divided by 2 (Figure 2).

For tree crop plantations, however, the carbon accumulation rates may not be linear throughout the entire rotation age of the system. The system may reach a maximum carbon stock (C_{max}) at a time (T_{max}) before the end of the rotation (T_r). As an example, a coffee plantation may reach the maximum carbon stock in 7 years but production continues for an additional 5 years, giving a rotation time (T_r) of 12 years, at which time the plantation is cut and re-established. In such cases the C accumulation rate (I_c) is determined by dividing C_{max} by T_{max}. This can only be determined if plantations that have reached maximum biomass have been sampled, and the age at which maximum biomass attained is known. For such systems, the time-averaged C stock for a land-use system is determined as the weighted average of the C stocks for the different phases of the rotation (Figure 3).

Calculation of the time-averaged carbon stock of the coffee plantation described above, with an establishment phase of 7 years to reach maximum biomass followed by 5 years of production before cutting and re-establishment will serve as an example (Figure 3). The values of $I_c = 2.2$ t C ha^{-1} y^{-1} and $T_{max} = 7$ were established from field data. The time-averaged C (C_{ta1}) for the establishment phase is equal to: $(I_c*T_{max})/2$ or 7.7 t C ha^{-1} for the 7 years. The time-averaged C for the remaining production phase (C_{ta2}) of 5 years is simply equal to C_{max} or 15.4 t C ha^{-1}. The time-averaged C for the entire system rotation ($LUSC_{ta}$) is the weighted average for the two phases:

$$[C_{ta1}* T_{max}] + [C_{ta2}* (T_r-T_{max})] /T_r = [53.9+77]/12 = 10.9 \text{ t C ha}^{-1}].$$

It is possible to compare the time-averaged C stocks of the different land-use systems within a site to that of the forest as a simple fraction or percentage of the forest biomass. To make cross-site comparisons of the systems it is necessary to include the original forest biomass at each site.

Appendix 3. Information used to calculate maximum C stocks (Cmax t C ha^{-1}), C accumulation rates (Ic t C ha^{-1} yr^{-1}), and land-use system time-averaged C stocks (LUSCta t C ha^{-1}).

A: Brazil

Information obtained from field measurements

Landuse	Reps	Age	Abvgrnd C stock	Standard deviation	AgeMaxC T_{max}	C accumulation rate, I_c	Standard deviation
Forest, logged	4	100.00	147.96	19.00	148	na	na
Fallow, natural	3	3.70	15.39	9.43	5	3.91	1.66
Fallow, improved	4	2.00	13.72	2.51	5	6.86	1.26
Pasture, traditional	4	11.00	5.69	3.43	2	2.85	
Pasture, improved	3	11.00	6.04	1.91	2	3.02	
Coffee, monocul	3	8.00	14.95	2.66	7	2.14	0.38
Multistrata	3	10.00	70.50	24.30	12	7.26	1.63

Calcuations used for estimating land use system time-averaged C stocks

LUS	CropC C_c	CropYrs T_c	Caccum I_c	FallowYrs T_f	Time Cmax	MaximumC C_{max}	Rotation T_r	C_{ta} CropPhs	C_{ta} FallowPhs	C_{ta} ProdPhs	LUS C_{ta}
Forest	-	-	-	-	-	148.00	-	-	-	-	148
Pasture/ traditional	-	-	2.85	-	2	5.70	-	-	-	-	2.85
improved	-	-	3.06	-	2	6.12	-	-	-	-	3.06
Crop/ natural fallow	2	3	3.91	5	5	19.55	8	2	9.78		6.86
low range	2	3	2.25	5	5	11.25	8	2	5.63		4.27
high range	2	3	5.67	5	5	28.35	8	2	14.18		9.61
Crop/ improved fallow	2.00	3.00	6.86	5	5	34.30	8	2	17.15		11.47
low range	2.00	3.00	5.60	5	5	28.00	8	2	14.00		9.50
high range	2.00	3.00	8.12	5	5	40.60	8	2	20.30		13.44
Crop/ coffee	2	2	2.14	-	7	14.95	12	2	7.48	14.95	10.93
low range	2	2	1.76	-	7	12.32	12	2	6.16	12.32	9.06
high range	2	2	2.52	-	7	17.64	12	2	8.82	17.64	12.83
Crop/ multistrataAF	2	2	7.26		12	87.12	20	2	43.56	87.12	61.18
low range	2	2	5.63		12	67.56	20	2	33.78	67.56	47.49
high range	2	2	8.89		12	106.68	20	2	53.34	106.68	74.88

B: Cameroon

Information obtained from field measurements

Landuse	Reps	Age	Abvgrnd C stock	standard deviation	Age MaxC T_{max}	C accum rate, I_c
Forest	5	100.00	228.00	27		.
Chromolaena	6	2.00	5.78	2.76	4	2.89
Midfallow	5	9.50	64.20	18.8	9	6.76
Oldfallow	7	18.50	130.92	37	23	7.26
Cacaoforest	5	25.00	88.72	31.6	25	3.55
Oilpalm	1	15.00	42.2		7	6.03

Calcuations used for estimating Land Use System time-averaged C stocks

LUS	CropC C_c	CropYrs T_c	Fallow Caccum I_c	FallowYrs T_f	Age maxC T_{max}	MaximumC C_{max}	Rotation T_r	C_{ta} CropPhs	C_{ta} FallowPhs	C_{ta} ProdPhs	LUS C_{ta}
Forest	-	-	-	-	-	228	-	-	-	-	228.00
Crop/ chromfallow	2.00	2.00	2.89	4		11.56	6	2	5.78	-	4.52
low range	2	2	1.51	4		6.04	6	2	3.02	-	2.68
high range	2.00	2.00	4.27	4		17.08	6	2	8.54	-	6.36
Crop/bush fallow	2.00	2.00	8.46	9		76.14	11	2	38.07	-	31.51
low range	2.00	2.00	6.24	9		56.16	11	2	28.08	-	23.34
high range	2.00	2.00	10.70	9		96.30	11	2	48.15	-	39.76
Shifting cultivation	2.00	2.00	7.26	23		166.98	25	2	83.49		76.97
low range	2.00	2.00	9.28	23		213.44	25	2	106.72		98.34
high range	2.00	2.00	5.24	23		120.52	25	2	60.26		55.60
Nonrotational cacao	-	-	-	-	-	88.72	-	-	-	-	88.72
low range	-	-	-	-	-	120.32	-	-	-	-	120.32
high range	-	-	-	-	-	57.12	-	-	-	-	57.12
Crop/cacao	2	2	3.55		25	88.72	40	2	44.36	88.72	61.10
low range	2	2	4.81		25	120.25	40	2	60.13	120.25	82.77
high range	2	2	2.29		25	57.25	40	2	28.63	57.25	39.36
Crop/oil palm	2	1	6.03		7	42.20	25	2	21.10	42.20	36.37

C: Indonesia

Information obtained from field measurements

Landuse	Reps	Age	Abvgrnd C stock	standard deviation	C accum rate, I_c	standard deviation	Age MaxC T_{max}
primforest	2	100.00	306.26	99	.		
logforest	4		93.20	41.3			
cassava	5	3.00	1.87	1.1	.		
imp	6	8.67	2.21	0.94	.		
treeplant	2	2.50	22.02	1.91	9.29	3.39	8
oldaf	4	25.00	89.15	39.8	3.55	1.26	25
oilpalm	1	8.00	63.20		9.03		7

Calcuations used for estimating Land Use System time-averaged C stocks

LUS	CropC C_c	CropYrs T_c	Fallow Caccum I_c	FallowYrs T_f	Age maxC T_{max}	MaximumC C_{max}	Rotation T_r	C_{ta} CropPhs	C_{ta} FallowPhs	C_{ta} ProdPhs	LUS C_{ta}
Forest	-	-	-	-	-	302.00	-	-	-	-	302
Logforest	-	-	-	-	-	93.20	-	-	-	-	93.20
Nonrotational	-	-	-	-	-	89.15	-	-	-	-	89.15
rubber system						128.95					128.95
						49.35					49.35
Crop/rubber AF	2.00	2.00	3.55	30	25	88.75	30	2	44.38	88.75	45.99
low range	2	2	1.98	30	25	49.50	30	2	24.75	49.50	25.71
high range	2	2	5.16	30	25	129.00	30	2	64.50	129.00	66.78
Oil Palm	0	0	9.03		7	63.20	25		31.60	63.20	54.35
Pulp plantation	0	0	9.29	8	8	74.32	8	0	37.16	-	37.16
low range	0	0	5.90	8	8	47.20	8	0	23.60	-	23.60
high range	0	0	12.68	8	8	101.44	8	0	50.72	-	50.72
Cassava/ imperata	1.87	7		3		2.21		1.87	2.21		1.97