ASB Lecture Note 4A

Carbon stocks of tropical land use systems as part of the global C balance:

effects of forest conversion and options for ‘clean development’ activities

Kurniatun Hairiah, SM Sitompul, Meine van Noordwijk and Cheryl Palm

INTERNATIONAL CENTRE FOR RESEARCH IN AGROFORESTRY

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Towards integrated natural resource management in forest margins of the humid tropics: local action and global concerns

Meine van Noordwijk, Sandy Williams and Bruno Verbist (Editors)

Humanity stands at a defining moment in history. We are confronted with a perpetuation of disparities between and within nations, a worsening of poverty, hunger, ill health and illiteracy, and the continuing deterioration of the ecosystems on which we depend for our well-being. However, integration of environment and development concerns and greater attention to them will lead to the fulfilment of basic needs, improved living standards for all, better protected and managed ecosystems and a safer, more prosperous future. No nation can achieve this on its own; but together we can - in a global partnership for sustainable development. (Preamble to the United Nations' Agenda21 on Sustainable Development; http://www.un.org/esa/sustdev/agenda21chapter1.htm).

Background to this series of lecture notes

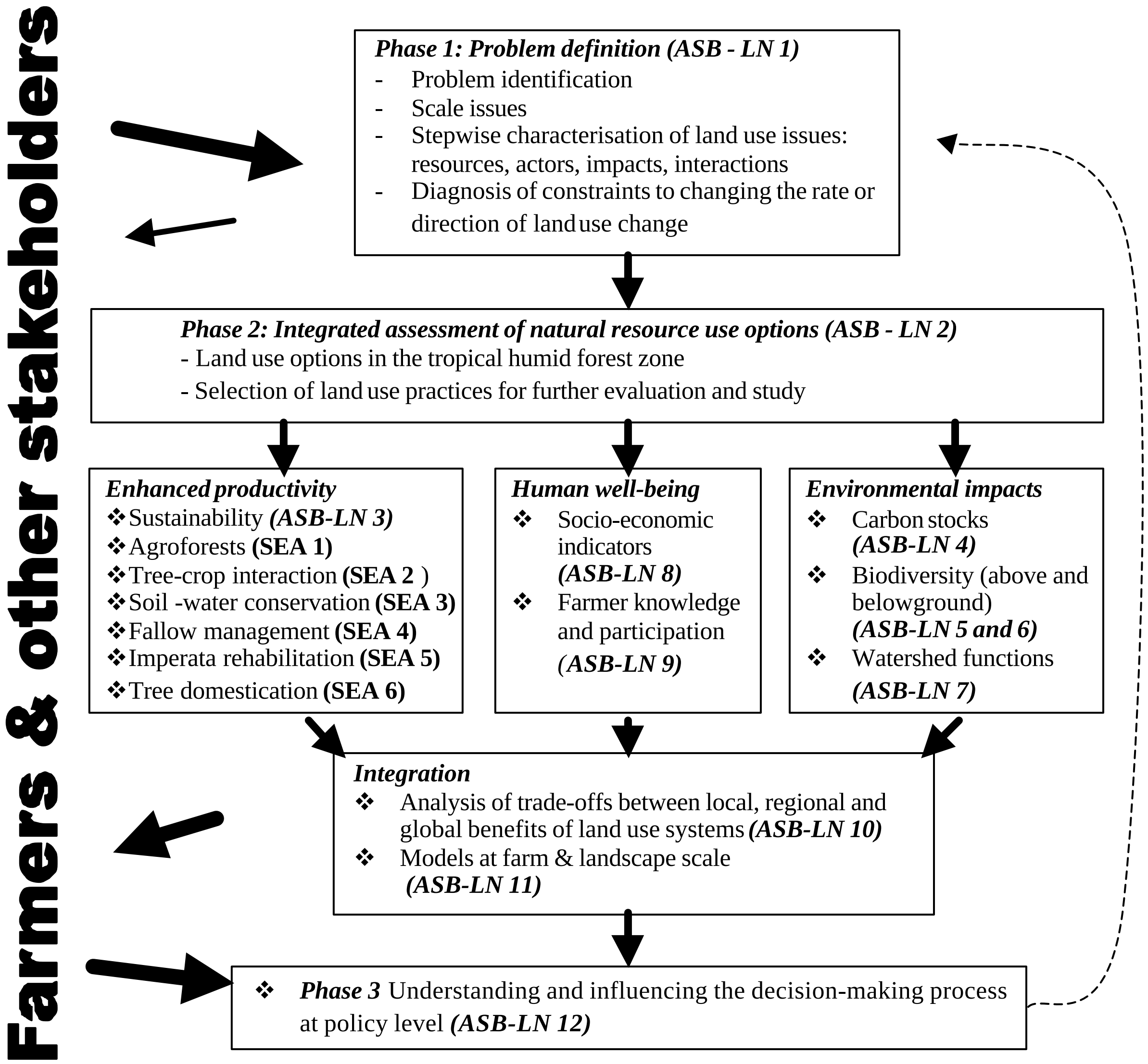
Much of the international debate on natural resource management in the humid tropics revolves around forests, deforestation or forest conversion, the consequences it has and the way the process of change can be managed. These issues involve many actors and aspects, and thus can benefit from many disciplinary perspectives. Yet, no single discipline can provide all the insights necessary to fully understand the problem as a first step towards finding solutions that can work in the real world. Professional and academic education is still largely based on disciplines – and a solid background in the intellectual capital accumulated in any of the disciplines is of great value. If one wants to make a real contribution to natural resource management issues, however, one should at least have some basic understanding of the contributions other disciplines can make as well. Increasingly, universities are recognising the need for the next generation of scientists and policymakers to be prepared for interdisciplinary approaches. Thus, this series of lecture notes on integrated natural resource management in the humid tropics was developed.

The lecture notes were developed on the basis of the experiences of the Alternatives to Slash and Burn (ASB) consortium. This consortium was set up to gain a better understanding of the current land use decisions that lead to ***rapid*** conversion of tropical forests, shifting the forest margin, and of the ***slow*** process of rehabilitation and development of sustainable land use practices on lands deforested in the past. The consortium aims to relate local activities as they currently exist to the global concerns that they raise, and to explore ways by which these global concerns can be more effectively reflected in attempts to modify local activities that stabilise forest margins.

The Rio de Janeiro Environment Conference of 1992 identified deforestation, desertification, ozone depletion, atmospheric CO_2 emissions and biodiversity as the major global environmental issues of concern. In response to these concerns, the ASB consortium was formed as a system-wide initiative of the Consultative Group on International Agricultural Research (CGIAR), involving national and international research institutes. ASB's objectives are the development of improved land-use systems and policy recommendations capable of alleviating the pressures on forest resources that are associated with slash-and-burn agricultural techniques. Research has been mainly concentrated on the western Amazon (Brazil and Peru), the humid dipterocarp forests of Sumatra in Indonesia, the drier dipterocarp forests of northern Thailand in mainland

Southeast Asia, the formerly forested island of Mindanao (the Philippines) and the Atlantic Congolese forests of southern Cameroon.

The general structure of this series is



This latest series of ASB Lecture Notes (**ASB-LN 1 to 12**) enlarges the scope and embeddes the earlier developed ICRAF-SEA lecture notes (**SEA 1-6**) in a larger framework. These lecture notes are already accessible on the website of ICRAF in Southeast Asia: http://www.icraf.cgiar.org/sea

In this series of lecture notes we want to help young researchers and students, via the lecturers and professors that facilitate their education and training, to grasp natural resource management issues as complex as that of land use change in the margins of tropical forests. We believe that the issues, approaches, concepts and methods of the ASB program will be relevant to a wider audience. We have tried to repackage our research results in the form of these lecture notes, including non-ASB material where we thought this might be relevant. The series of lecture notes can be used as a basis for a full course, but the various parts can also ‘stand alone’ in the context of more specialised courses.

Acknowledgements

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ASB-consortium members

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Lecture Note 4A

CARBON STOCKS OF TROPICAL LAND USE SYSTEMS AS PART OF THE GLOBAL C BALANCE: EFFECTS OF FOREST CONVERSION AND OPTIONS FOR 'CLEAN DEVELOPMENT' ACTIVITIES

By Kurniatun Hairiah, S.M. Sitompul, Meine van Noordwijk and Cheryl Palm

Contents

I. Objectives

- To describe the causes of climate change and to discuss the role of tropical forests in this
- To discuss the impacts of land use changes on C stocks at two levels: global and plot level
- To understand why farmers practice slash-and-burn
- To illustrate how coherent sets of measurements can be made to evaluate options for 'clean development' in tropical land use
- To simulate the impacts of land use changes on C stocks based on the CENTURY 4.0 model.

II. Lecture

1. Why are the global C cycle and C stocks important?

1.1 Climate change: an introduction

Around 1890, Arrhenius, a Swedish chemist, was the first to predict a quantitative increase in global temperature (of 5 to 6 degrees Celsius) due to a doubling of the atmospheric concentration of CO2 resulting from the use of fossil fuel. But to him, living in Sweden, this could only have a positive effect on human livelihoods. In a 1908 paper he remarked: "By the influence of the increasing percentage of carbonic acid in the atmosphere, we may hope to enjoy ages with more equable and better climates, especially as regards the colder regions of the Earth, ages when the Earth will bring forth much more abundant crops than at present for the benefit of the rapidly propagating mankind" (Christianson, 1999).

In the 100 years since then, have Arrhenius' predictions come true? And have attitudes changed? Certainly, in the last two decades, global temperature has increased steadily, and this has corresponded with a sharp increase in atmospheric CO2 concentrations (Figure 1). During the last 10 years the possibility that human activities can, and do, change climates all over the earth, has moved from the realms of a scientific debate to the general recognition that this change needs to be controlled, and to an international convention that tries to do so (UNFCCC- the United Nations Framework Convention on Climate Change).

What causes climate change?

Greenhouse gases

The main impacts on the global climate are caused by changes in the composition of the atmosphere, because the atmosphere influences the balance between incoming radiation from the sun and outgoing heat from the earth. This effect of the atmosphere is similar to that of a glass roof, allowing sunlight to come in but reducing radiative heat loss to outer space, hence the terms 'greenhouse effect' and 'greenhouse gases' for the major gases in the atmosphere that are responsible for this.

The main concern is over greenhouse gases such as **carbon dioxide (CO_2)**, **methane (CH_4)** and **nitrous oxide (N_2O)**. Chemical reactions between these gases in the atmosphere are still only partly understood, but a prominent role of the three gases mentioned above is beyond reasonable scientific doubt. Water vapour is actually one of the strongest 'greenhouse gases', but its presence in the atmosphere is in a natural (although dynamic) equilibrium between evaporation and rainfall, and there are no indications of long term changes that are directly due to human activity. Furthermore, not all gases in the atmosphere contribute to the greenhouse effect (Box 1).

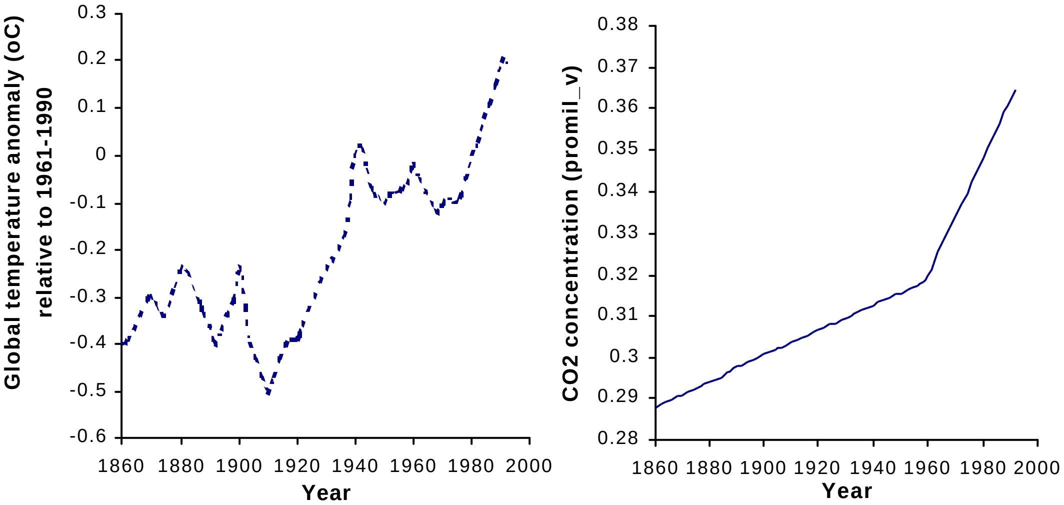


Figure 1. Global temperature relative to the average for the 1961-1990 period and atmospheric CO2 concentration (ml l-1) since 1860 (source: Watson et al., 1995).

Box 1 Counter-effects

A number of other gases, sulphur dioxide (SO_2) for example, are also now recognised as partly counteracting the effects of greenhouse gases. In fact, the drop in industrial SO_2 emissions after 1970, which was the successful response to the environmental problem of acid rain, may actually have made the greenhouse effect stronger (and may partly explain why global warming has increased since then).

What IS important, however, is that human activities can lead (and have led) to a net increase in atmospheric concentrations of the three important greenhouse gases carbon dioxide (CO2), methane (CH4) and nitrous oxides (N2O and NO). These activities include:

- conversion of forest (or other natural or manmade vegetation) to other land uses ('land use change'), where one-off events involved in the change of state, such as burning, result in substantial gaseous emissions,
- land use as such, where agricultural practices, for example, can lead to gas fluxes that differ from those under natural vegetation (and these effects operate over the long term as well as directly after the land use change), and
- burning of fossil fuels, in industry and for urban consumption and transportation, which causes increased gas emissions.

In this lecture note we focus on the first and second as they relate to tropical land use and forest conversion -- this does not mean, however, that these two categories are the main overall concerns...

Land cover change (LCC)

In addition to greenhouse gases, there are other ways that human activities have an impact on the climate. The main one is via the albedo or the amount of sunlight that is reflected at the surface of the earth, rather than absorbed by the vegetation. Land cover change will change the albedo, especially where green plant surfaces are replaced by non-plant surfaces.

Predicting climate change and its effects

Climate (the long term average conditions on a site) and weather (current conditions) are difficult to predict, as they are the outcome of many interacting processes, with many opportunities for a small disturbance to be magnified and become a hurricane of change. A number of global circulation models (GCMs) exist that agree on overall directions of change at global scale, yet differ in their details regarding predictions of change for specific parts of the earth.

From a local perspective, people (such as Arrhenius, above) may see climate change as an improvement, especially in the colder parts of the earth and it may increase options for agriculture. Overall, however, the change is seen as being a very risky experiment with the planet Earth, and we don't have another planet to escape to if the experiment goes wrong. One of the likely consequences of global warming is a melting of polar ice caps and a rise in sea level, as has happened in geological history. Such a rise will wipe a few small island nations off the map of the earth, and will affect some of the most densely populated and fertile coastal areas, such as Bangladesh and parts of SE Asia. Technical solutions such as higher dykes, stronger pumps and so on could, in theory be used, but would require huge investments.

Climate change will be first of all a 'climate shift'. For agricultural practices it may be possible to just follow the shifting climate ('shifting the cultivation systems of the earth'), with some countries or regions gaining and other losing. This by itself is likely to cause conflicts if not wars, even if the total food production capacity is not diminished. For natural vegetation and fauna, however, the rate of change of the local climate may be too fast, especially as the domains available for the world's biodiversity have tended to become a set of 'islands' of national parks in a 'sea' of an agriculturally-used landscape. So, many plants and animals will not be able to follow the shifting climates.

From the current understanding of the earth as an interconnected system of land masses, oceans and atmosphere, it seems likely that change can happen in two ways:

1. As a gradual, relatively predictable process of overall warming, and
2. As a step-wise process where rapid reorganisation of, for example, oceanic currents (such as those involved in the El Niño effect) can lead to much more rapid and dramatic change.

Thresholds for this latter type of change are hard to predict, but if we take a 'don't believe it until you have seen it' approach we will almost certainly be too late to respond.

The global debate on details of the climate change process continues, but there is little reasonable doubt that reducing the net emissions of carbon-dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O and NO) is imperative to keep the rate of change within a range that will allow human adaptation.

In this lecture note, most of our discussion will focus on CO_2, as it dominates the debate especially where land use change is concerned, but we will come back to CH_4 and nitrous oxides in section 1.6.

1.2 The global carbon cycle

The emergence of life on earth has led to the conversion of carbon dioxide (CO_2) that was in the atmosphere and oceans, into innumerable inorganic and organic compounds on land and in the sea. The development of life on earth in different ecosystems over million of years has established patterns of C flows through the global environmental system. Natural exchanges of C between the atmosphere, the oceans and terrestrial ecosystems are now being modified by human activities and changing land use. Human activity has led to a steady addition of CO_2 to the atmosphere and an increase of the atmospheric concentration from 285 ppmv (parts per million on a volume basis) before the industrial revolution of the 19th century to 336 ppmv in 1998. This is an increase of more than 28 % of its value, over the past 150 years. The current increase in concentration corresponds to an average annual C accumulation (over the last 10 years) of 3.3 Gt yr^{-1} (1 giga ton = 10^9 t = 10^{15} g).

Stocks

In the global C cycle (Figure 2), the first thing to look at is the current **stock** (capital). By far the greatest proportion of planet's C is in the oceans; they contain 39 out of the 48 Tt of C shown (1 tera ton = 10^{12} t = 10^{18} g). The next largest stock, fossil C, accounts for only 6 Tt. Furthermore, the C stocks in all the forests, trees and soils of the world amount to only 2.5 Tt, whilst the atmosphere contains only 0.8 Tt.

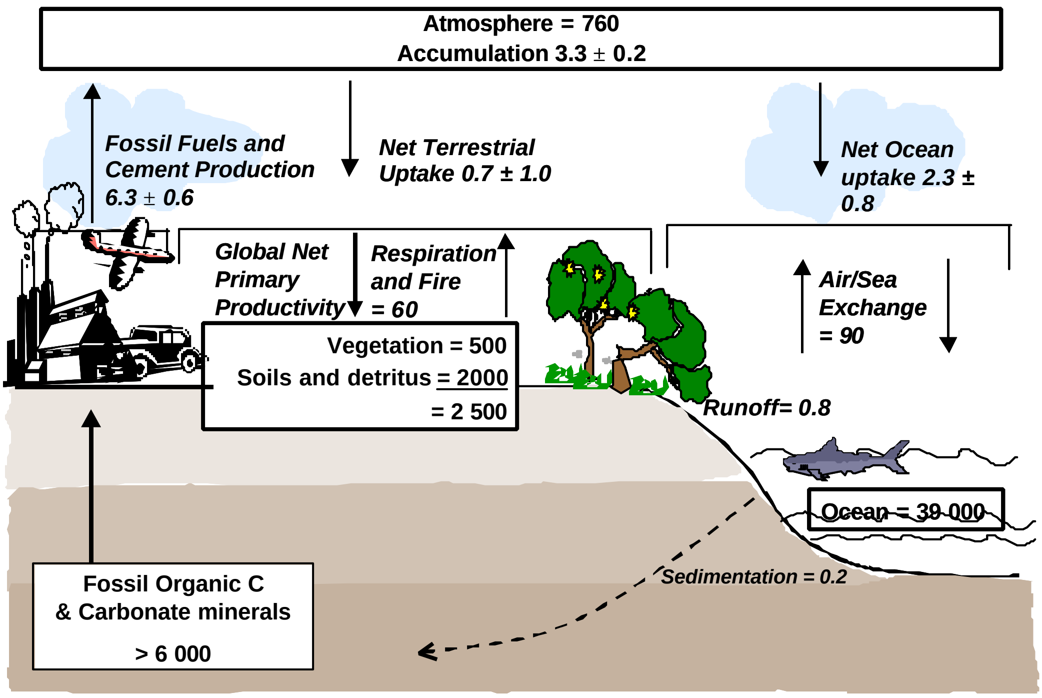


Figure 2. The global C-cycle showing the C-stocks in reservoirs (in Gt = 1015g = 109 ton) and C flows (in Gt yr-1) relevant to anthropogenic disturbance, as annual averages over the decade from 1989-1998 (Schimel et al., 1996, cited in Ciais et al., 2000).

Fluxes/changes

The simple story is that the use of fossil fuels (and cement) releases 6.3 Gt C yr^{-1}, of which 2.3 is absorbed by the oceans and 0.7 by terrestrial ecosystems, and the remaining 3.3 is added to the atmospheric pool. Fossil organic C is being used up much faster than it is being formed, as only 0.2 Gt C yr^{-1} of sedimentation can be seen.

The net uptake by the oceans is small relative to the annual exchange between atmosphere and oceans: oceans at low latitudes (in the tropics) generally release CO_2 into the atmosphere, while at high latitudes absorption is higher than release.

Similarly, the net uptake by terrestrial ecosystems of 0.7 Gt C yr^{-1} is small relative to the flux: about 60 Gt C yr^{-1} is taken up by vegetation, but almost the same amount is released by respiration and fire. Over the last few decades the tropical ecosystems have been net releasers of C, mostly because of forest conversion, while at high latitudes C uptake has been more than C release. Forests at high latitudes have recovered from previous heavy exploitation, while there has been some CO_2 fertilization effect as plant growth was stimulated by higher CO_2 concentrations in the atmosphere. The relative magnitude of this CO_2 fertilization effect is still debated. Terrestrial vegetation and soils contain about three and a half times as much C as the atmosphere; the exchange is controlled by photosynthesis and respiration.

Soil is a major C pool in all biomes, whereas C-stocks in vegetation are essentially restricted to the forest biomass. Globally, soils store much more C than vegetation (Figure 2)-- but in the tropics this is only true for peat swamp forests and non-forest land uses. The C reserves of the peat soils of the subarctic zones are huge -- but they are at risk if temperatures increase.

QUESTIONS

Where are the main C pools? What are the largest fluxes?
Where are the largest net C-sinks?
What is the problem? Who could do something about it?

If we extrapolate current flows to the future, we have, first of all to consider the release of C from fossil fuels. If this would continue at an ever-increasing rate, as development increases the energy use per capita and the world population continues to grow, it will lead to huge changes in atmospheric CO_2, way before the total stocks are depleted (NB many of these stocks are, however, not economically exploitable at current technologies and prices). So, a stabilisation and reduction of total C release from fossil fuel is urgently needed -- the hottest issue then is one of equity between countries: developing countries see it as their right to increase their fossil fuel use to reach per-capita emissions that are equal to those in the rest of the world; countries with high per-capita use want to stabilise emissions at the current level per country. This is the core of the current international debate, and relates to the ‘Clean Development Mechanism’ (section 5).

C-sinks (sequestration)

In the meantime, the oceans and the land masses (terrestrial ecosystems) can play a role (Figure 2). Net C uptake by the oceans has been the main buffer that has slowed down increase of atmospheric CO_2 so far. The oceans actively exchange CO_2 with the atmosphere, predominantly in the form of dissolved inorganic C. Ocean uptake of C is limited, however, by the solubility of CO_2 in sea water and the slow rate of mixing between surface and deep ocean water. For the biological component in net C uptake, questions of pollution control, especially in the main sink areas of the ocean are clearly important. One of the factors that apparently controls the biological activity in the surface metre of the oceans that is responsible for most of the net C uptake, is the nutrient, and especially iron (Fe), inflows from terrestrial systems (e.g. dust from deserts...).

Net C uptake by terrestrial ecosystems can play a buffering role, but it is smaller than the role of the oceans. An important point in the current discussion is that C stored this way will be vulnerable to release back into the atmosphere. As current efforts to control emissions, even if they would be adhered to, are definitely not sufficient to stop global warming (they only reduce the speed at which this occurs), the future release of terrestrial C stocks into the atmosphere is an uncertain but potentially important element in the debate. Just looking at the size of the current pools and fluxes, one would get the impression that increased C storage in terrestrial systems could be a real contribution to solving the problem of increased atmospheric CO_2 concentrations. However, over time the risks that this stored C will return to the atmosphere will increase. Existing models that synthesize the best of our ecological process knowledge, already predict that with continued increase in atmospheric CO_2 and temperature, the CO_2 fertilization effect will come to an end while respiration will increase, making the terrestrial systems a net source of C.

Clearly, banking on increased C uptake in trees and forests while continuing a business-as-usual approach to fossil fuel use is risky and unwise. But, terrestrial sinks can play a relevant role in the transition of the global human economy in finding cleaner ways of deriving its energy requirements. Substitution of fossil fuels with newly produced biomass can be an alternative, but only in as far as the fossil fuel remains unexploited and safely protected from oxidation in deep soil layers.

In summary, the problem is that the annual C-release to the atmosphere from fossil fuel use is larger than the rate at which the oceans can absorb CO_2 plus the rate at which terrestrial ecosystems act as a sink. The consequence is an increased CO_2 concentration in the atmosphere that contributes to global warming, which in its turn can drastically change local climates by modifications in atmospheric circulation systems.

The questions are:

- Which land use patterns can play a significant role in **conserving existing C stocks** (especially forests) and **increasing the net storage of C** in terrestrial ecosystems?
- At **what time scale** can such effects operate?
- Is there a **risk of future release** into the atmosphere of additional C storage in terrestrial systems?

Factors that influence the net terrestrial uptake of C include the direct effects of land use and land use change (e.g. forest conversion and change in agricultural practices) and responses of terrestrial ecosystems to CO2 fertilization, nutrient deposition, climatic variation, and disturbance e.g. forest fires.

Clearing forest for new agricultural land causes a release of C to the atmosphere. The C initially held in trees and other vegetation is released through burning (in the form of smoke) or decomposition of above and below ground plant material left in the soil at the time of clearing. Even if the gross and net primary productivity (see Box 2) of the new agricultural land is as high as it was in the forest, less of the crop production accumulates as litter, most of it is harvested and subsequently consumed or respired away from the land where it was grown. This makes the 'net ecosystem productivity' much lower. The reduction in litter input is not initially balanced by a reduction in soil respiration. In fact, the respiratory release is often enhanced by the cultivation itself, which exposes more of the organic matter to microbial activity and thus causes a net release of nutrients to the crops (and weeds). As a result, some of the C originally held in forest soil is released to the atmosphere after clearing. The C stocks maintained in aboveground biomass, however, do differ between forest and a cropped field, as does the rate of litterfall, leading to differences in soil organic matter (SOM) in soils.

A better understanding of the relations between C stocks and land use practices is required in the context of the global C balance. The impacts of the ongoing processes of land use change need to be assessed and efforts to store more C in terrestrial ecosystems need to be evaluated, in terms of their ability to slow down the rate of increase of atmospheric CO2. Data on soil C stocks are particularly needed at the scale of implementation projects for the Clean Development Mechanism (section 5) and at the scale of similar attempts to stimulate C storage in the process of development. Both of these scales are substantially above the conventional scale of soil analysis and sampling, and the research approach must be based on stratification and recognition of domains of similarity, one way or another.

A reduction in organic inputs to the soil and/or accelerated losses after forest conversion lead to a decline in the more active ('labile') C fractions in the soil. These changes influence crop productivity at a localised scale as well as the global C budget. So, to some extent, the interests of the farmer in maintaining soil fertility may coincide with interests at the global level in reducing the rate of increase of atmospheric CO2. In this lecture note, we will consider the local as well as global aspects of changes in C stock.

Primary production by plants can be measured at different levels, as explained in Box 2. Where carbon credits are involved, there is always a danger that the increments at the level of net ecosystem productivity are counted on the positive side, while the losses by harvest and disturbance are conveniently ignored…

1.3 Carbon sequestration and time-averaged C stock

The C sequestration potential of terrestrial ecosystems depends on the type and condition of the ecosystem- that is, its species composition, structure and age distribution (especially for forest). Site conditions are also important e.g. climate and soils, natural disturbances and management.

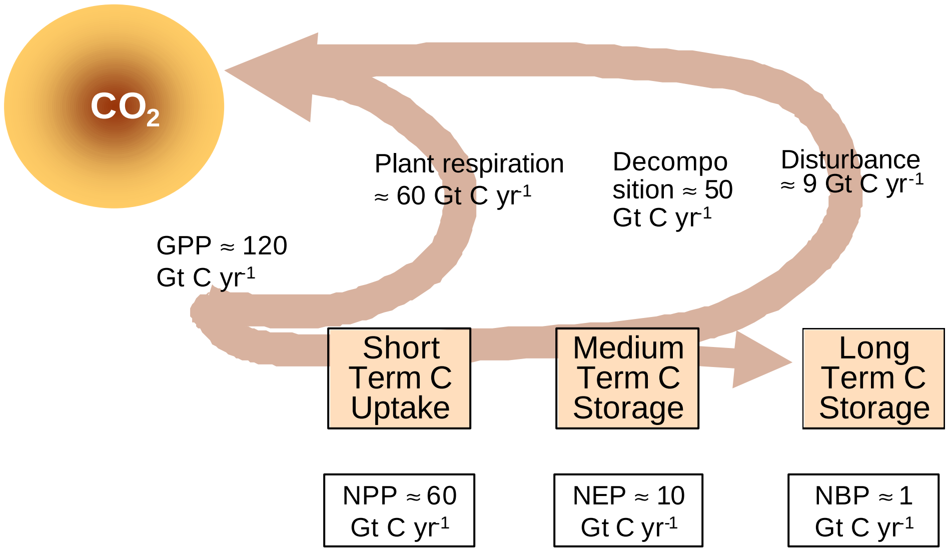
Carbon is removed from the atmosphere annually in younger ecosystems, such as forest plantations or in forests regenerating from the impacts of logging, fire or other disturbance. The impressive biomass accumulated within a mature, tropical rain forest may lead one to expect that this ecosystem continues to accumulate C. Although this is true for the individual trees within the forest it is not the case for the forest as a whole. This is because decomposition rates of carbon in a mature forest are (approximately) equal to carbon fixation rates. (An exception to this rule is the accumulation of organic soil horizons in swamp forests on peat soils.)

Decomposition is thus a key issue. Once carbon has been fixed by vegetation, how long does it stay that way, before turning back into carbon dioxide as a result of decomposition or burning? The concept of a half-life of carbon (the time, in years, taken for half of the mass of carbon to decay) can be used, and this can be estimated for different parts of the vegetation (e.g. 0.3 for leaf litterfall, 1 for branch litterfall, 4 for dead wood and around 20-30 years (as an order of magnitude) for live wood).

Carbon sequestration is often defined as the (semi) permanent removal of C from the atmosphere. So, carbon sequestration may be defined as:

the net annual C productivity (NPP) (Mg ha^{-1} year^{-1}) multiplied by the expected half-life (in years) of carbon fixed

Box 2. Book-keeping of terrestrial C based on flows or stocks at different time scales



For the analysis of C budgets, the fundamental differences between GPP, NPP, NEP and NBP must be recognised (Figure 2). The quantitative global flux estimates are as follows:

- *Gross Primary Production (GPP)* denotes the total amount of C fixed in the process of photosynthesis by plants in an ecosystem, such as a stand of trees. GPP is measured on photosynthetic tissues, principally leaves, on a hourly time scale and integrated to a year. Global total GPP is about 120 Gt C yr^{-1}.
- *Net Primary Production (NPP*) denotes the net production of organic matter by plants in an ecosystem, NPP is about half of GPP as plants respire the other half in building up and maintaining plant tissues. NPP can be measured as the increase in plant biomass on a daily or weekly time scale. For all terrestrial ecosystems combined, it is estimated to be about 60 Gt C yr^{-1}.
- *Net Ecosystem Production (NEP*) denotes the net accumulation of organic matter or C by an ecosystem; NEP is the difference between the rate of production of living organic matter and the decomposition rate of dead organic matter (heterotrophic respiration). Heterotrophic respiration includes losses by herbivory, and the decomposition of organic matter by organisms. Global NEP is estimated to be about 10 Gt C yr^{-1}. NEP can be measured in two ways: one is to measure changes in C stocks in vegetation and soil over time, an annual time scale; the other is to integrate hourly/daily fluxes of CO_2 into and out of vegetation and integrate up to the yearly time scale. NEP should be integrated up to a decadal (10 year) time scale.
- *Net Biome Production (NBP)* denotes the net production of organic matter in a region containing a range of ecosystems (a biome) and includes, in addition to heterotrophic respiration, other processes leading to loss of living and dead organic matter (harvest, forest clearance and fire etc.). Compared to the total fluxes between atmosphere and biosphere, global NBP is comparatively small: 0.7 ± 1.0 Gt C yr^{-1}. It can be measured only at a decadal or longer time frame, as the disturbances that are to be taken into account don't occur every year. The discussion of which disturbances are 'natural' and which are at least partly caused by humans is complex where fire is involved.

The dimensions of C sequestration thus are Mg ha^{-1}, and it is therefore a system characteristic and no longer a rate (Mg ha^{-1} $year^{-1}$).

There are some complex issues that arise from the use of this definition of C sequestration, and these are discussed below.

If the carbon fixed in wood or other plant products is harvested and removed from the plot, the half-life of its C content is modified, i.e. either decreased (as in the use of firewood) or increased (e.g. when wood is conserved chemically, by using it in a dry environment or storing it under water). A difficulty with our definition of C sequestration is that the C sequestration attributed to a system largely depends on what happens to the products of that system elsewhere. The half-life of wood depends on its use as firewood or timber and on any subsequent wood conservation methods.

A considerable part of the C fixed by crops is transported from the field at harvest to markets in urban areas where it is in turn consumed and readily decomposed. If urban waste treatment methods were modified to conserve this C, conventional agriculture would become an important mechanism for sequestering C. We may thus have to modify the boundaries of the systems considered, and cannot attribute C sequestration to a land use system, without regard to the next steps in the food chain.

This definition of C sequestration shows that the annual rate of CO_2 release into the atmosphere by burning fossil fuels can only be off-set by C sequestration if:

- the area involved, or
- the half-life of the products or
- the net C productivity

keeps increasing.

We may want to put an upper limit on the half-life of products to be considered. Otherwise, the formation of charcoal (which has a nearly infinite half-life) would come out as by far the best C sequestration method, even though only a small fraction of forest C is transformed into charcoal when forests are burned.

In addition, mature forests do not (or hardly) sequester carbon according to this definition, once they have reached the equilibrium where the formation and breakdown of the relatively long-lived components are in balance. In a natural forest, individual patches will continue a cycle of gap formation when a large tree falls and of regrowth until one of the many saplings that enters the race for light in the gap becomes a tree as big as the one that just fell. A forest as a whole is a mosaic of patches and will reach a balance between C losses and gains, if the gap formation is due to small-scale local processes. Yet, in parts of the world where forest renewal is dominated by larger events (cyclones, hurricanes, fire), the whole forest will be more synchronised and a longer time frame is needed to establish the equilibrium between losses and gains. The difference between NEP and NBP (Figure 3) then becomes important, and this is reflected in the debate about whether the Amazon is a C sink or not. Measurements of C in mature forests in C. America and the Caribbean islands appear to show C stocks increasing with time, although we must remember that these forests nearly always seem to be in a state of recovery from the last hurricane.

To avoid these complexities of the definition and measurement of C sequestration, we will here focus on the quantification of the C stocks that are actually present in a patch of land that belongs to a certain land cover class, or to a land use system (see lecture note 2), that comprises various types of cover during its life time.

We thus obtain an entity of the same dimension as C sequestration: ton (or Mg) of C per ha, instead of a rate (Mg ha^{-1} yr^{-1}). We may seem to miss something: the fate of all C rich products that are harvested or otherwise removed from the plot. But, these products have to go somewhere - especially to the cities and other urban or industrial areas and their waste dumps. If we make sure that the assessment of current C stocks includes all the land area of the globe, we will come across the wooden houses, the wooden furniture, the stack of old newspaper, the landfills and waste disposal sites and any other form of prolonged life of C that was initially sequestered outside of the urban areas. This can be easily included in our book-keeping system this way, so we do not need to attribute it to the land where it was originally removed from the atmosphere. It would simplify the debate if such a procedure were to be followed -- but the global C book-keepers of the world have not yet dared to take this step, and continue to account for the global trade flows of wood products, with all the ensuing complications...

For this lecture note, we will focus on the C stocks that are actually present on the land, averaged over the lifecycle of a land use system. This is called the time-averaged C stock. Referring back to Figure 3: if we were to measure C fluxes on an hourly basis as gross primary productivity (GPP) and plant respiration, we have to deal with very large numbers in either direction, and the uncertainties in the measurement will make it difficult to assess the small difference between losses and gains. The relevant time scale for us is the net biome productivity (NBP), but we may have to approach this by measuring the net ecosystem productivity (NEP) and account for the 'disturbances' (that include harvests) separately. The key then is to be able to quantify the current (on-site) C stock at any stage of the life cycle of a land use system (Box 3).

1.4 The time-averaged C stock of a rotational production system

Most agricultural, agroforestry or forestry production systems go through distinct phases in their production cycle. If we don't want to deal with the details of C gains and losses within each patch in each year, we can assume that the time-averaged C stored in each patch under the land use system (averaged over the rotation time of that system, Figure 4 and Box 3) represents the spatial average for all patches at any point in time. The time-averaged C stock depends on:

- The maximum and minimum C stored in the system, typically just before and just after a harvest event,
- Rates of C accumulation during the growth phase, which implies the time it takes to reach maximum C stocks from the minimum level, and
- The rotation time.

If we can assign a typical 'time-averaged Carbon stock (Mg ha^{-1}), to each land use type, the net impact of land use change follows from the sign of the difference of '**Cstock(after) – Cstock(before)**'. This means that an evaluation of the C stock of a land use depends on the context and the types of comparisons made: compared to natural forest, all other land use types lead to net C release to the atmosphere; compared to continuous annual crops, nearly all other land uses lead to net C sequestration.

Box 3. How to determine time-averaged C-stocks?

To determine the time-averaged C stock of a land use system, we need to know the C stock at any point in time. In the simplest case, we can describe this as:

- a period T_c where it is at minimum value C_{min} (e.g. a cropping period after forest clearing or a harvest cycle)
- a period where carbon accumulates linearly, at a constant rate I_c (Mg C ha^{-1} yr^{-1}), from the minimum value C_{min} to the maximum value C_{max} in a time span of T_f. (thus $I_c = (C_{max} - C_{min})/T_f$).

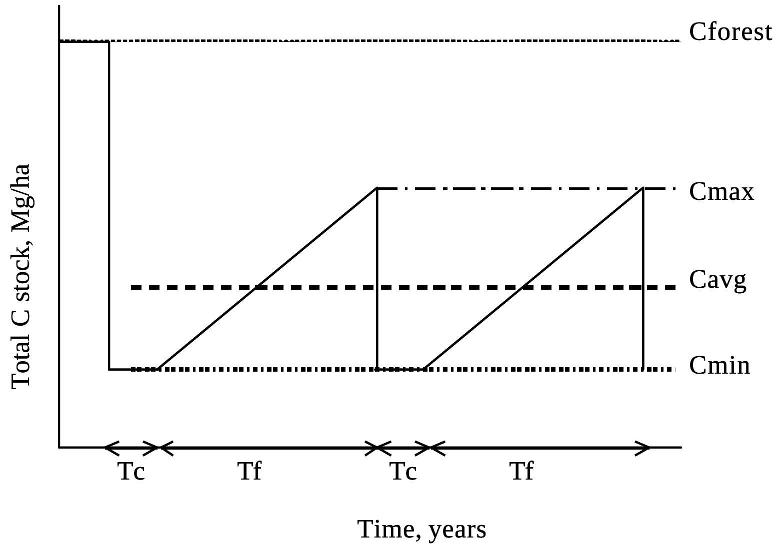


Figure 3. Diagram of C losses during forest clearing and re-accumulation during a fallow or regrowth period T_f after the cropping years T_c (Palm *et al.*, 1999)

The time-averaged C stock for the period T_f is $C_{avgF} = 0.5 * (C_{min} + C_{max})$
For the system as a whole it is:

$$C_{avg} = T_f * (C_{max} + C_{min})/(2*(T_f + T_c))$$

where:
C_{min} and C_{max} are the minimum C stocks of the system, respectively,
T_c is the length of time the system is at the C_{min} value, and
T_f is the length of time that it takes to reach C_{max}.

If T_c is negligible, we see that $C_{avg} = 0.5 (C_{max} + C_{min})$, and thus independent of the time T_f or the annual accumulation rate.

This means that fast growing (timber) trees will have the same time-averaged C stocks as slow growing trees, if they are harvested at the same standing biomass (same C_{max} an

Box 3. How to determine time-averaged C-stocks? (continued)

For tree crop plantations or some agroforestry systems, however, the maximum carbon stock (C_{max}) may be reached at a time (T_m) before the end of the rotation (T_r). As an example, a coffee plantation may reach the maximum carbon stock in 7 years (establishment phase) but production continues for an additional 5 years (production phase), giving a rotation time (T_r) of 12 years, at which time the plantation is cut and re-established. The time-averaged C stock for such land-use systems is determined as the average of the C stocks for the different phases of the rotation (Figure 4).

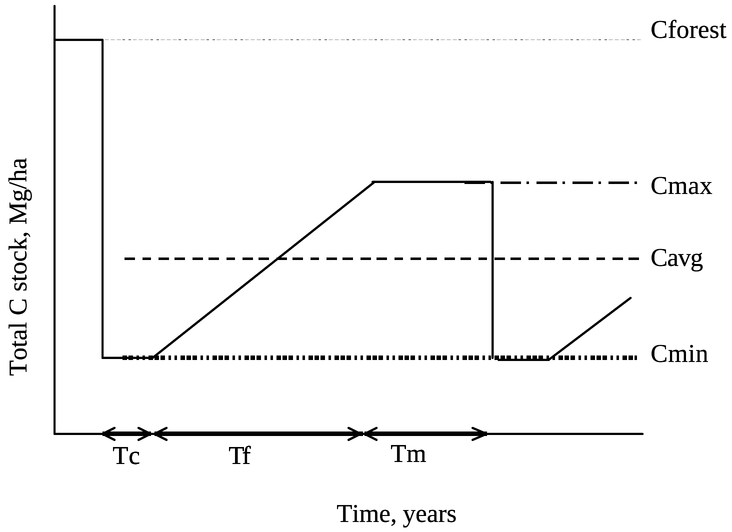


Figure 4. Diagram of above-ground C losses after harvest and re-accumulation during establishment of tree-based production system

As before, the time-averaged C stock for the period T_f is $C_{avgF} = 0.5 * (C_{min} + C_{max})$
For the period T_m that the C stock is at its maximum it is simply C_{max}
For the system as a whole it is:
$C_{avg} = (T_c * C_{min} + 0.5 * T_f * (C_{min} + C_{max}) + T_m * C_{max}) / (T_c + T_f + T_m) =$
[crop phase] [establishment phase] [production phase] [total length of system]

To simplify calculations, this can be written as:
$C_{avg} = [(T_c + 0.5 * T_f) * C_{min} + (0.5 * T_f + T_m) * C_{max}] / (T_c + T_f + T_m)$
where T_m = the period that the system is maintained at its maximum C stock C_{max}

Example:

Calculation of the time-averaged C stock of a coffee plantation, with an establishment phase of 7 years to reach maximum biomass followed by 5 years of production before cutting and re-establishment. The values of $I_c = 2.2$ Mg C ha^{-1} yr^{-1}, T_f 7 year and $C_{min} = 0$ are consistent with a C_{max} value of 15.4 Mg ha^{-1}.

Time-averaged C stock (C_{ta1}) for the establishment phase $= (I_c * T_f)/2 = C_{max}/2 = 7.7$ Mg ha^{-1}.

The time-averaged C stock for the entire system rotation is the weighted average for the three phases:

$= [0 + 7*7.7 + 5*15.4]/12 = (3.5 + 5) * 15.4/12 = 10.9$ Mg ha^{-1}

So, the establishment of timber plantations can lead to a net sequestration of C if it replaces a low C stock system such as a grassland, or lead to a loss of C if it replaces a depleted/logged-over forest that still has a C-stock that is higher than the time-averaged C stock of the plantation.

Once again: C-sequestration is not a property of a land use system as such, but the consequence of the change from one type of system to another.

The approach that we present here for deriving 'time-averaged C stocks' can be used for assessments at national scale, as is shown more formally in Box 4 on Global C Accounting.

Two counter-intuitive consequences

Erosion and charcoal formation are two issues that have caused confusion in the debate on C sequestration. ***Erosion*** has often been included in lists of factors leading to C loss. However, erosion leads to a transport and redistribution of soil material, not to losses from the global ecosystem. Relocation of soil organic matter by erosion may actually conserve C, as soil carbon becomes protected from decomposition processes in acidic swamp environments or in fresh-water and marine sediments. Potentially, erosion may thus contribute to C sequestration, provided that the landscapes remain vegetated and maintain their gross primary productivity. From this perspective, land management techniques, which seek to reduce soil loss may be at odds with broader objectives of C sequestration…

Charcoal formation leads to long term storage of C, even if only a fraction of the woody biomass is converted to charcoal in a fire. If the forest regrows and the charcoal from the previous vegetation remains, the time-averaged C stock will increase. So, is burning the forests of the world to create charcoal and stimulating erosion and sedimentation in lakes the solution to the global C problem? Maybe we have the time-scale wrong

Box 4. Global C- accounting

The methodology recommended by the International Panel on Climate Change (IPCC) is based on a simple concept, namely that the total terrestrial C stock at any time ***t*** is equal to *the product of the area fraction* under each of a set of mutually exclusive ‘land uses’ and a typical C stock value associated with that land use at time *t*. It may help to write this down formally, so we are aware of the assumptions and simplifications made. Let

$$A_t = \sum_{i=1}^{n} A_{i,t} \qquad (1)$$

be the total area of a unit of land (e.g. a country or part thereof), which is allocated to *n* different land uses, that are mutually exclusive. We can define area fractions a_{it} as:

$$a_{i,t} = A_{i,t} / A_t \qquad (2)$$

The total C stock at time *t* is now defined as:

$$C_t = \sum_{i=1}^{n} A_{i,t} C_{i,t} = A_t \sum_{i=1}^{n} a_{i,t} C_{i,t} \qquad (3)$$

Box 4. (Continued)

where $C_{i,t}$ is the C stock per unit area under land use *i* at time *t*, and the change in C stock over an interval *t -> t+1* as:

$$\Delta C_{t->t+1} = A_{t+1} \sum_{i=1}^{n} a_{i,t+1} C_{i,t+1} - A_t \sum_{i=1}^{n} a_i C_{i,t} \tag{4}$$

If the total area does not change (so $A_t = A_{t+1}$) and the land use classification is the same, this means that the net C sequestration or emission is defined as:

$$\Delta C_{t->t+1} = A_t \left(\sum_{i=1}^{n} (a_{i,t+1} C_{i,t+1} - a_{i,t} C_{i,t}) \right) \tag{5}$$

This equation can be re-written to separate a term indicating change in average C stocks per unit area within the class *i*, and a term reflecting the change in area of class *i*:

change in average C-stock in class *i*

change in area for class *i*

$$\Delta C_{t->t+1} = A_t \left(\sum_{i=1}^{n} (a_{i,t} (C_{i,t+1} - C_{i,t}) + (a_{i,t+1} - a_{i,t}) C_{i,t}) \right) \tag{6}$$

The current IPCC methodology is based on equation (6) and includes estimates of increments of average C stock within a land use class. Much of the uncertainty of current national inventories derives from the assumptions made about these increments. There is a tendency to count the increments but ignore the losses. For assessments at national scale the assumption that the various stages of a land use system will 'average out' may be acceptable, unless the average age of trees or forests within a class increases or decreases.
We can simplify the accounting procedure by 'packaging' specific sequences of C stocks (such as in shifting cultivation, sustainable selective logging or crop-fallow rotations) into 'land use systems', with a 'time-averaged C stock', C_i that are independent of time. Equation (6) simplifies to:

$$\Delta C_{t->t+1} = A_t \left(\sum_{i=1}^{n} C_i (a_{i,t+1} - a_{i,t}) \right) \tag{7}$$

This means that the change in C stock can be assessed from the change in the area fraction of the various land use practices, multiplied with a time-averaged C stock for each of these classes.

Exercise:
Calculate the time-averaged C-stock for a *Paraserianthes* (fast growing pulp tree) plantation, if the values of the C accumulation rate I_c = 9 Mg C ha^{-1} yr^{-1} and the length of a production cycle (T_f) = 8 years, and T_{max} and T_c = 0.
What is the value for a slower growing tree with I_c = 4.5 Mg C ha^{-1} yr^{-1} and a production cycle of 16 years?

What is the C_{max} value for each system?

Questions for group discussion:
- Will planting trees always contribute to increased C storage? When will it not?
- Which strategies would you prefer to reduce CO_2 in the atmosphere? Why?

1.5 Land cover and land use

We can now revisit the relations between land cover and land use (see lecture note 2), in relation to deriving time-averaged C stocks. The Kyoto protocol only refers explicitly to two types of land cover: '**forest**' and '**non-forest'**. Although attractive for its simplicity and general appeal, this dichotomy does not stand up to scrutiny when terrestrial C stocks are to be quantified, as the aboveground **C stock in forest can range from 20 to 400 Mg C^{-1} ha^{-1}**. This is even if we exclude an extreme case such as a cassava field that could legally be classified as 'forest' because a cassava plant could, technically, be defined as a 'tree' (see lecture note 1).

Clearly, if we are concerned about the storage of C in terrestrial ecosystems we will have to collect data for land cover classes that are more homogenous than 'forest'. Natural forest vegetation differs in typical C stocks with climate and soil, and thus with elevation and latitude. In almost every zone a 'forest degradation' series can be found, with increasing intensity of harvesting of forest products and reduced C stock. Changes in intensity of use, without changes in forest cover per se, can have a substantial impact on C stocks. For example, selective logging often removes the largest individual trees, and it is these that constitute a significant proportion of the C stocks per hectare.

Figure 5 relates a 'land cover' classification to C stocks and shows that 'land use' systems can consist of various types of cover during different phases of each cycle. The time-averaged C stock of a land use system depends on the C accumulation rates in different stages of the cycle, as well as on the duration of each stage.

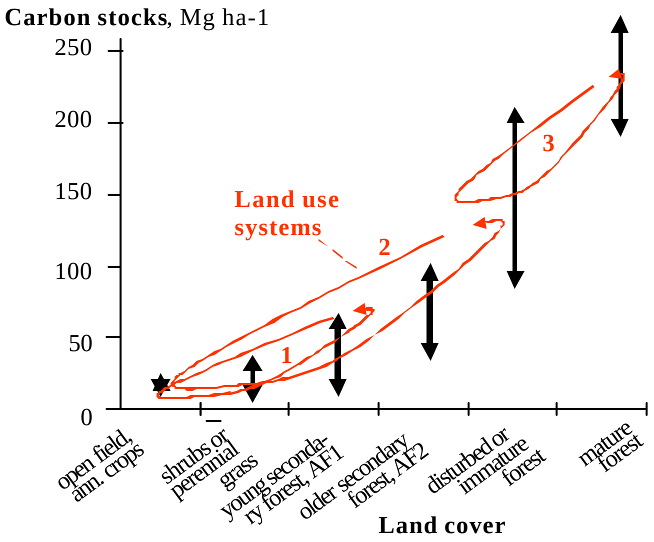


Figure 5. Relationships between land cover, land use systems (that contain various land covers in different stages of their life cycle) and C stocks; land use systems 2 and 1 reflect long and short fallow rotation systems, 3 selective low-impact logging; AF1 = simple agroforestry systems, AF2 = complex agroforests

For shifting cultivation and crop-fallow rotations (Figure 6), the time-averaged C stock decreases with increasing intensity of land use. In a C accounting system based on Equation (6) (see Box 4), we conclude that:

> '<u>Shifting cultivation'</u> as a land use <u>does not</u> lead to C sequestration or C release into the atmosphere, HOWEVER ...
> '<u>Intensification</u>' of land use within this system <u>does lead</u> to net release of C.

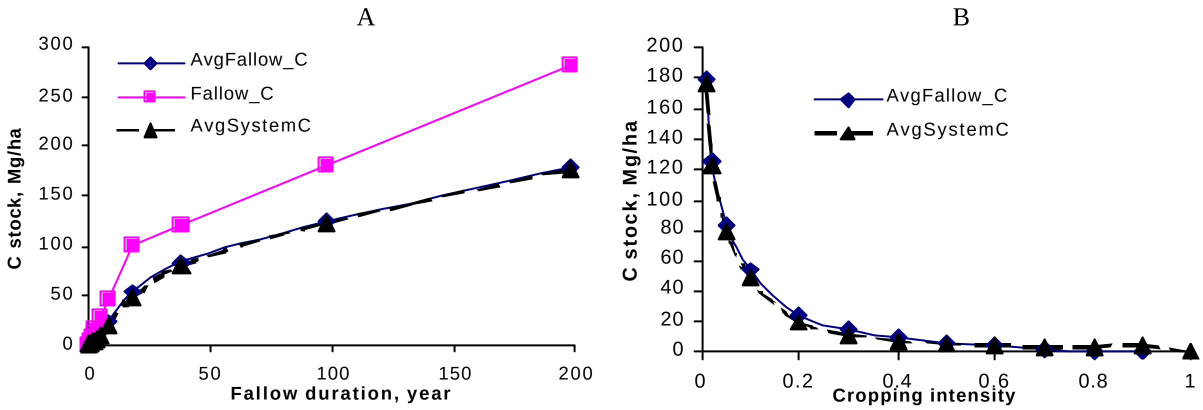


Figure 6. Time-averaged C stock of shifting cultivation and crop-fallow rotation systems, as a function of (A) fallow duration and (B) cropping intensity (= fraction of area cropped in any year), for an annual C stock increment during fallow years of 6 Mg C ha^{-1} year^{-1} up to 100 Mg C ha^{-1} and 1 Mg C ha^{-1} year^{-1} beyond that; assuming 2 years of cropping per cycle.

1.6 The other greenhouse gases

Methane, CH_4

Methane is formed by bacteria during the breakdown of organic matter in the absence of oxygen, for example in wet soil, under water, or in the rumen of herbivores. Methane molecules can still be used by bacteria as a source of energy in other circumstances where oxygen is available, so the pathway between the methane source and the atmosphere determines whether or not emissions take place. Methane is formed in wet soils, but if it diffuses to the atmosphere through layers of soil where oxygen is present, most of it can be broken down before it reaches the surface. If however, it encounters roots of wetland plants such as rice, with their internal air channels, it can reach the atmosphere via these ‘chimneys’ -- that's why growing rice can increase methane emissions to the atmosphere. In marshes methane can come to the surface in bubbles of 'marsh gas' (this can be trapped and used for cooking, just as the gas from organic waste fermenters or landfill sites can be captured and used).

So the replacement of natural wetlands by rice paddies can lead to increases as well as decreases in methane emissions, but the creation of wetland rice paddies in conditions where the soil would otherwise have had enough oxygen, definitely increases methane emissions to the atmosphere. Total concentrations of methane in the atmosphere are smaller, by a factor of 200, than those of carbon dioxide, but the current relative annual increase is twice as fast as that of CO_2. The overall greenhouse gas effect per molecule of methane is considered to be greater, by a factor of 26, than that of CO_2 when evaluated over a 20 year period.

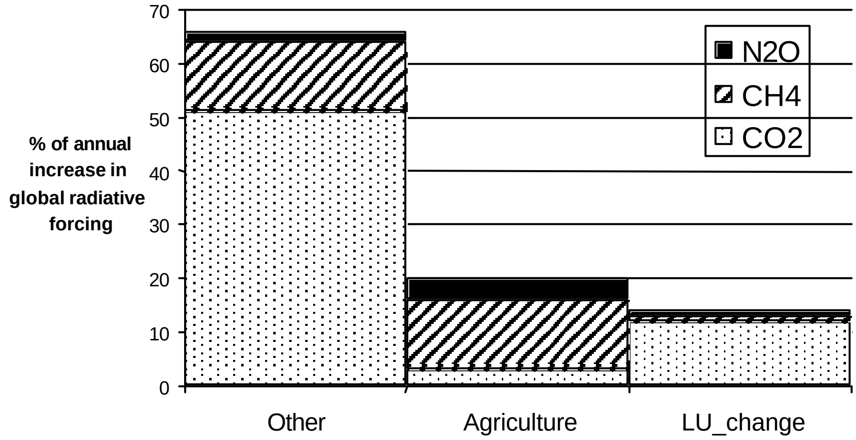


Figure 7. Proportions of the annual increase in global radiative forcing that are due to agriculture, land use change and other (industrial, urban, transport) activities (Watson *et al*., 1995).

Atmospheric concentrations of methane have increased substantially over the last century, and the major causes are considered to be:

- industrial emissions and leaking gas pipes,
- burping cows: increased livestock numbers,
- emissions from an increasing area of wet ricefields that are kept wet for a larger portion of the year (as more crops are being grown per year),
- increased burning of organic wastes and increased use of fire in forest clearing, where the smouldering stage especially leads to methane emissions,
- a reduction in methane consumption by soils, especially those of forests which usually have an open, spongy structure (i.e. a low 'bulk density').

Overall, agriculture is responsible for about half of the annual increase in the atmospheric methane concentration (Figure 7).

Nitrous oxides, N_2O

Like methane, nitrous oxides are formed by the process of denitrification under conditions of low oxygen supply, in wet soils, with the ratio between N_2O and NO depending on the conditions. Denitrification activity is generally assumed to be proportional to the soil N content, and thus increases when manure or fertilizer is added to soils. Inefficient car engines, where incomplete combustion occurs, also produce a lot of nitrous oxides.

The total concentration of nitrous oxide N_2O in the atmosphere is smaller by a factor of 1000 than that of carbon dioxide and the relative annual increase is two thirds of that of CO_2, but the 'greenhouse gas effect' per molecule is a factor 206 greater (evaluated over a 20 year period).

Atmospheric concentrations of nitrous oxides have increased substantially over the last century, and the major causes are considered to be:

- combustion engines,
- emissions from soils due to denitrification, especially from wet soil rich in nitrogen due to inorganic or organic fertilization,
- emissions during fires related to land use change

Emissions during slash-and-burn fires

Fires used for land clearing after forest conversion lead to emissions of methane and nitrous oxides as well as the fine particulate organic material that is the main cause of 'haze'. The fraction of total biomass that is emitted in these forms depends on the type of fire, and especially on the ratio between 'flaming' and 'smouldering' phases of the fire. If the fuel is wet a larger part of it might be left behind as unburned or partially burnt residue (and charcoal), but a larger fraction of the amount that was burnt is emitted as one of the gases or as small particulate matter. As everyone who has used wood in a fireplace or for cooking knows, hot fires using dry fuels tend to be cleaner, as more complete oxidation takes place. Overall, the total emission factor has to be integrated over the phases of a fire, as a wet/damp fuel load can be dried by the heat pulse ahead of the flames, before it actually catches fire itself.

Importance of methane and nitrous oxide emissions relative to changes in C stocks

Globally, while agriculture is responsible for about 20% of the annual increase in radiative forcing (the greenhouse gas effect) and land use change is responsible for 14% (Figure 7), the situation in the margin of tropical forests is different. There, changes in C stock completely dominate the issue (Box 4). If, however, paddy rice fields or intensively fertilized upland crop fields are formed, annual emissions of methane and nitrous oxide may, over time, become more important than the once-only change in C stock caused by the initial deforestation.

Box 5. Case study: Greenhouse gas emissions measured by ASB Indonesia

Measurements of the net flux of methane and nitrous oxide were made in a wide range of land use systems. Scaling up from point measurements to typical fluxes over the life span of a land use system (similar to the time-averaged C stock) is not yet possible, however. Day/night as well as seasonal rhythms have to be considered to derive annual flux data, which should be combined for the year of forest clearance and slash-and-burn, early re-growth etc.

Table 1 summarises the flux data obtained in the wet and dry season for the land uses studied within the ASB project. Methane oxidation rates were higher in the dry than in the wet season. The low level of NH_4 and NO_3 in *Imperata* and cassava might have caused the low N_2O emission from those land-use systems. Data on N-mineralisation, therefore, have to be analysed to explain the difference in terms of nitrification or denitrification pathways. For the current analysis we explored the relationship between net methane flux and soil bulk density, and between nitrous oxide emission and soil mineral N concentration, both modified by water-filled pore space at the time of observation. Both relationships were weak, and may not form a sufficiently strong basis for extrapolation between measuring points.

Data for methane oxidation and nitrous oxide emission can be compared on the basis of their 'net radiative forcing' (NRF) CO_2 equivalent values (26 and 206, respectively). It is obvious that removing above-ground carbon stock from forested land or tree-based systems will have a greater effect on global warming than that caused by soil emissions. For the natural forest and rubber monoculture plots studied, the overall effect on net radiative forcing is negative (this means less global warming, as more methane is oxidised than nitrous oxide emitted in NRF equivalents). For the other land uses, nitrous oxide emissions will have a bigger impact on the greenhouse properties of the atmosphere than the methane oxidation.

Box 5. (Continued)

Table 1. Summary of net greenhouse gas emission effects from current land use (methane and nitrous oxides) and land use change (carbon, allocated to a 25 year period). *n.a.= not applicable; *= no data*

Land use system	Time averaged C stock, Mg ha^{-1}	Mean seasonal net methane absorption, mg m^{-2} h^{-1}		Mean seasonal net N_2O emission, $\mu g\ m^{-2}\ h^{-1}$		Net radiative forcing (C equivalents) mol m^{-2} yr^{-1}		
						soil emis-sions	LU conversion (25 years)	
		Wet	Dry	Wet	Dry		from forest	from Imperata
Natural forest	254	0.036	0.046	12.9	1.80	-0.03	0	n.a.
Community-based forest management	176	*	*	*	*	*	26	n.a.
Commercial logging	150	0.044	0.050	17.8	3.60	0.06	35	n.a.
Rubber agroforests	116	0.035	*	34.6	2.97	0.71	46	-26
Rubber agroforests with clonal material	103	*	0.029	*	3.06	0.61	50	-22
Rubber monoculture	97	0.009	0.060	6.1	0.43	-0.06	52	-20
Oil palm monoculture	91	*	*	*	*	*	54	-18
Upland rice/ bush fallow rotation	74	*	*	*	*	*	60	-12
Cassava/*Imperata* rotation	39	0.001	0.018	9.4	*	0.24	72	0

2. Why are farmers interested in C stocks?

Farmers deal with the reality of above- and belowground C stocks, but from a rather different perspective than the one we have discussed so far. To them above-ground C stocks (trees) are a source of tree products (fruits, resin, timber or firewood), a marker of land ownership claims, a modifier of the microclimate by providing shade, a link to the spiritual world and so on.

Below-ground C stocks consist of plant root systems and soil organic matter. Farmers consider the below ground C-stock as a source of tree products (e.g. for medicinal purposes and for furniture), they are also considered as a source of **soil fertility**, either in the short or long term (chemically, physically and biologically) see lecture note 6.

However, farmers often destroy the aboveground C stocks on their land, by literally sending them up in smoke. They use slash-and-burn techniques to prepare agricultural land, by cutting and burning all the understorey and small and medium sized trees, although some of the larger trees may be left standing. This is the preferred method of land clearing in SE Asia for smallholders and large companies alike, because it is cheap and easy. This activity is normally carried out in the period of least rainfall; the vegetation is cleared using an axe or machete, left to dry, and burned shortly before the first rains.

From a global-C perspective, if we want to induce farmers to maintain or re-establish larger C stocks e.g. by not burning, or by planting more trees, we have to first understand the farmers' perspectives on the C stocks and on the transformations between them. Boxes 6 and 7 show how important this can be when communicating with farmers about C-related issues.

Box 6. Can farmers estimate C stocks on their land?

If efforts to increase terrestrial C stocks by introducing new land use practices are to succeed, it is important that farmers, as the primary land users, are aware of at least the orders of magnitude involved. If any financial compensation schemes come into effect to induce farmers to maintain higher C stocks, criteria for this should relate to farmers' concepts and knowledge. As most of the C stocks in humid forest systems are aboveground, we explored the categories that farmers use to assess the size of trees. Are these categories just 'small – medium – big' or are they more sophisticated?

Informal discussions with farmers in Jambi (Sumatra) inside their rubber agroforest showed clearly that they are used to assessing the volume of timber in <u>m^3 of wood</u> (per 0.25 m^3 increment), as it is used in the market. It appeared, however, that the concept of '<u>volume</u>' for them is directly linked to the commercial value. Trees without commercial wood value had no 'volume' in the farmers' language either. The simple message is thus that as soon as financial 'value' will be attached to the trees that are currently not marketable, one way or another, farmers may start to see their other trees as valuable too.

Box 7. What's in a word?

In the surveys that were part of the Characterization phase of the ASB project (see lecture note 1) in Indonesia, we asked about the ways that farmers plant their rubber. The answers we got only referred to the technique based on slash-and-burn clearing of the land. Later on, we found that many farmers are also using an '<u>interplanting</u>' practice where they plant rubber into gaps in existing rubber gardens, or they actively create such gaps once young rubber trees are established. This no-burn system appears to be a perfect way to reduce greenhouse gas (GHG) emissions. Why didn't we hear about these practices earlier?

In the Indonesian language the word '<u>tanam</u>', which is the normal translation of planting, refer to <u>'planting into bare land' only</u>, while the word for interplanting is <u>'sisipan'</u>. So instead of asking a neutral, generic question, we indicated interest in only one of the two ways to plant trees, and missed a relevant part of the story for quite some time.

Planting tree crops such as rubber into existing vegetation, instead of into a field cleared by slash-and-burn, is desirable from the point of view of people who are interested in conserving C stocks and decreasing GHG emissions. But what factors determine whether farmers themselves choose to do this? We must consider the disadvantages to the farmer (e.g. slower growth due to shade, no opportunity to grow rice) as well as the advantages (e.g. less demand for capital and labour), and try to understand how farmers weight these factors when making decisions about land uses which may have very different C stocks.

Question

- Forest conversion by slashing and burning reduces the C-stock. Why do farmers do this? Can't they do it differently?

2.1 Why farmers burn

Most farmers say "No fire, no farms", because fire gives them benefits through:

1. Provision of free fertilizer via ash
2. Improvement of soil structure
3. Elimination of field debris, making it possible to walk around in the plot
4. Reducing regrowth of weeds. Most understorey plants are killed by the burn and the ground is left completely clean, free of weeds and ready for planting the first crop
5. Reducing pest and disease problems

-- Ash as fertilizer: effect of burning on soil nutrients

Most of the nutrients in the slashed fallow or forest vegetation, except N and S (sulphur) are preserved and added to soil in the ash. Many researchers have reported post-burn increases in pH and some of the major basic cations. Although C and N losses from the aboveground biomass can be large, C and N losses from the soil are generally none or very small (Andriesse, 1989).

The effects of the burning on soil fertility are influenced by two factors:

- Large quantities of *nutrients* from the standing vegetation and the litter layer are spread in the ash on the surface of the soil.
- The immediate soil surface is *heated*, and this has some direct effect on the chemical properties (especially phosphorous (P) availability), soil physical properties and the microbiological population.

The effects of burning on characteristics of a forest soil are shown in Box 8.

The magnitude of the increase in soil nutrients is usually related to the age of the forest cleared. However, because increase in nutrient storage in old forest takes place predominantly in woody materials and much of this may not be readily combustible, the soil fertility benefits do not keep increasing with longer fallow period. The thoroughness with which the burn is carried out will also determine to some extent the quantities of nutrients added to soil.

--Burning improves soil structure

More severe burns may alter the fundamental physical characteristics of the soil. A high-intensity fire significantly increased soil bulk density in top layer 0-5 cm from 0.83 $\pm$ 0.03 kg dm^{-3} to 0.90 $\pm$ 0.03 kg dm^{-3} (Ketterings, 1999). Medium to low intensity fires did not affect the soil bulk density. The increase in bulk density upon intense heating can be explained by the combustion of organic matter, which leads to the soil shrinking.

Box 8. Case study from N. Lampung

Data from North Lampung (Indonesia) were collected on the direct effects of burning on ash and soil nutrient content. The ash layer on top of the soil was sampled from a 25 year-old secondary forest, and soil was sampled separately for the top 3 cm and the 3-5 cm layer. The ash layer consisted of burned plant material and fine charcoal as well as true ash. Table 2 shows that soil pH was increased by at least two points, due to accumulation of base cations which came from the burnt above-ground biomass (ash).

Table 2. Chemical properties of forest soil before and after burning in N. Lampung (van Noordwijk *et al.,* 1998).

Soil layer	pH		C_{org}	P-Olsen,	K^+	Ca^{2+}	Mg^{2+}
Cm	H_2O	KCl	%	mg kg^{-1}	cmol$_c$ kg^{-1}		
Before burn:							
0 - 5	6.2	4.7	2.44	5.0	0.20	1.44	0.62
5 - 10	5.6	4.6	2.12	2.0	0.20	1.85	0.52
After burn:							
0 - 3	8.1	7.5	7.15	51.4	5.37	25.5	4.47
3 - 5	8.3	7.2	4.28	25.6	2.02	14.8	3.46
5 - 10	7.2	6.0	1.94	6.7	0.29	3.12	0.63
Soil surface ash				384	176	23.6	17.6

Although ash addition enhanced the pH increase, heat exposure was responsible for a large part of the reduction in Al-toxicity (Ketterings, 1999). At the deeper soil layer 5-15 cm only soil C decreased.

Exchangeable cation content as well as available P content increased dramatically; these studies, once again, demonstrate that slash-and-burn methods are an *effective* way of supplying available nutrients to the following vegetation/crop.

2.2 Reduction of C stocks related to land clearing techniques

Question

- After cutting and burning the forest, is there any biomass left in the field?
- How much C is lost during the burning? And how much is left if there is no burn involved?

Not all vegetative biomass is lost during burning; the amount, which is left can depend on:

a) humidity, which is related to the time of day, the afternoon usually being drier than in the morning

b) position on the slope (as a fire front moves more easily uphill than downhill),

c) wind (as greater windspeeds ‘fan’ the fire, bringing in more oxygen which helps the fire to burn hotter/more intensely).

Box 9. Case study: effects on C-stocks of clearing secondary forest for agriculture, with and without burning (Prayogo *et al.*, 2000)

C-stock measurements were made in Jambi province, Sumatra in two secondary forest plots (Forest I and Forest II) which were then cleared by farmers who then planted rubber trees. There were two treatments:

- Forest I: Slashing and burning
- Forest II: Only slashing, no burning.

Burning reduced total C in the system by about 66 %, in contrast to a reduction of only about 22 % when no burning (only slashing) was involved (Figure 8). In the no-burn plot, some of the C stocks from the original vegetation still remained, and existed mainly as big branches (on the soil surface), tree trunks, and some living trees which farmers had kept. Very little change was observed in the C-stock in the soil after forest conversion in either of the treatments (Prayogo *et al.*, 2000).

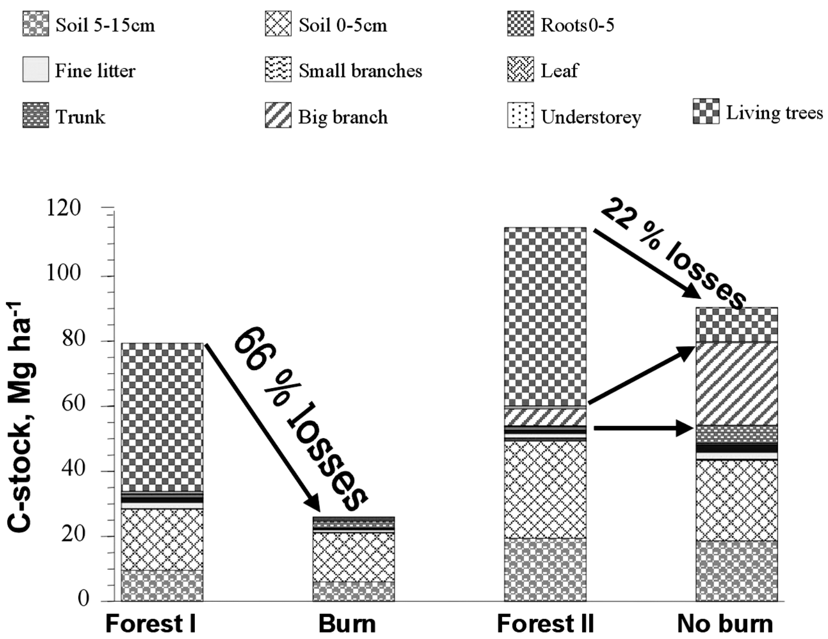


Figure 8. Carbon stocks of two secondary forest plots before and after slashing (in addition, Forest I was burned, but Forest II was not).

2.3 Carbon in soil: how is it lost or gained and who cares?

Forest conversion to agricultural land leads to a **reduction** of soil C stocks, mainly caused by agricultural management i.e. residue removal via harvesting or burning, and soil tillage.

The C content of agricultural soils has generally been depleted in repeated cropping periods by 20-50 % relative to their original condition. This removal of C from the soil causes severe degradation of soil fertility (Hairiah et al., 2000).

Most C enters ecosystems via leaves, and C accumulation is most obvious when it occurs in above-ground biomass. However, more than half of the assimilated C is eventually transported below-ground via root growth and turnover, oxidation of organic substances from roots, and incorporation of fallen dead leaves and wood (litter) into soil (Figure 9).

Net **accumulation** of soil organic matter occurs through practices that increase the amount of plant-fixed C that is returned to soils in the form of residues (leaves, stems, branches and roots). Litter will be decomposed by organisms responsible for forming soil organic matter (SOM). Roots make a relatively large contribution to soil organic matter due to their location in the soil, and linkage to soil particles. So, the soil organic matter is composed of decomposing residues, by-products formed by biota responsible for decomposition of the residues, the micro-organisms themselves, and the more resistant soil humates.

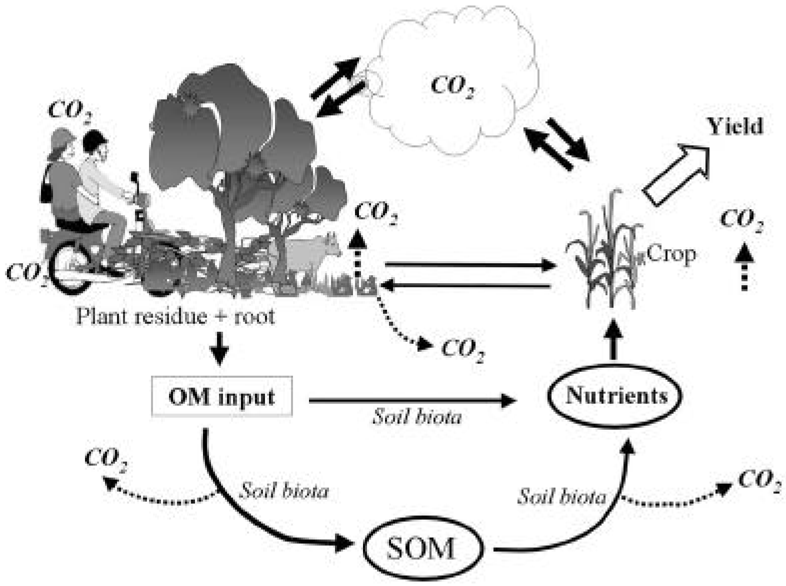


Figure 9. The C cycle at the farm level.

--Why should farmers care about soil organic matter?

Soil organic matter plays a key role in crop production under the low-external input conditions prominent in the humid tropics. Recently the role of soil C storage for the global C budget has been considered a topic of equal importance. Figure 10 shows schematically the roles of soil organic matter in cropping systems and its dynamics that merit special interest from those who seek to improve the sustainability of cropping systems, especially in the humid forest zone (Van Noordwijk et al., 1997). The production and deposition of organic materials provide substrate for microbial processes and the accumulation of soil organic matter. The processes associated with the incorporation and transformation of soil organic matter directly affect the constraints to plant productivity such as soil acidity (toxicity), soil erosion and water and nutrient availability.

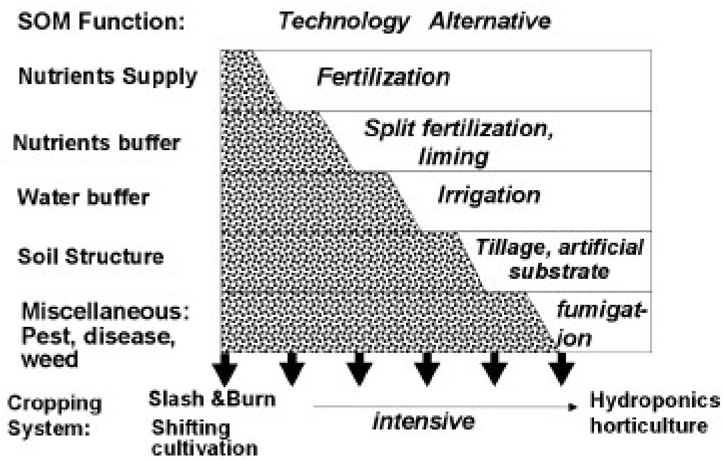


Figure 10. Soil organic matter (SOM) functions and the technological alternatives that can replace them in crop production systems of different intensity

For all the roles of soil organic matter, technical alternatives exist and today's hydroponic horticultural systems (for growing crops without any soil organic matter, or even without soil) show that this is not only possible, but even economically attractive under certain conditions. Yet, for the vast majority of tropical farmers these technical substitutions are not feasible and soil organic matter still fulfils all the above functions. A 'shadow price' of soil organic matter might be based on the price of the technical substitutes which are not (or less) necessary if soil organic matter levels are maintained.

Many of the positive effects of agricultural practices such as ploughing, drainage and liming on crop yields result from accelerated breakdown of soil organic matter. A conflict thus exists between the role of organic matter as source of nutrients and its other roles. When not replenished, soil organic matter functions as a non-renewable resource and slash-and-burn (migrant) farmers may be tempted to follow or create new forest margins and leave a zone of depleted soil behind. In the humid tropics of Asia, such lands are generally occupied by grasses such as *Imperata cylindrica*, which may partly restore the soil, or at least prevent further degradation.

3. Carbon stock measurements

In sections 1 and 2 of this lecture note, we have seen that data on C-stocks can be used:

- to directly assess the *current* C stocks in above and belowground pools in plots that represent a certain land cover, as part of a land use system,
- to *extrapolate* to the 'time-averaged C stock' of a land use system.

C stock data can also be used to initialise simulation models (such as CENTURY) which can explore C dynamics with respect to land use change and the subsequent effect on the global climate (section 4). Furthermore, biodiversity and profitability assessments can be compared with C stock data to study trade-offs among global environmental benefits and private incentives to the farmer (lecture note 10).

Two types of methods are used to measure losses or accumulation of C on land: methods that measure stocks of C and methods that measure fluxes. Although a brief account of flux measurements is given in Box 10, the emphasis in this section, however, is on measuring stocks of C in the vegetation of forest, agricultural crops, and fallow systems.

Box 10. Carbon flux measurements

The direct exchange of CO_2 between vegetation and atmosphere is a two-way process, as the gas is both absorbed and given off by the vegetation. This means that the fluxes are difficult to separate out and measure. The main methods are based on the so-called 'eddy-correlation' technique. Air flow is generally turbulent and 'eddies' consist of upward and downward flows of air. By using sensors to measure the CO_2 concentration in the air at timescales of seconds and separating the periods with upward movement from those with downward movement, the net flux can be calculated, throughout the day and night. Integrating these measurements to make an annual budget, however, is no trivial task…

As discussed previously (Figure 2, section 1.2) global C can be divided into several C pools: ocean, terrestrial, atmospheric and miscellaneous C pools. In this section, the term 'carbon stocks' is used for the C stored in terrestrial ecosystems (the terrestrial C pool), namely that stored in plant biomass (above and below-ground) and in the soil. Table 3 illustrates the components of the terrestrial C pools. Above-ground biomass comprises all woody stems, branches, and leaves of living trees, creepers, climbers, and epiphytes as well as understorey plants and herbaceous undergrowth. For agricultural lands, this includes crop and weed biomass. The dead organic matter pool (necromass) includes dead fallen trees, other coarse woody debris, litter and charcoal.

The below-ground biomass comprises living and dead roots, soil fauna, and the microbial community. There also is a large pool of organic C in various forms of soil humus (soil organic C, SOC). Other forms of soil C are charcoal from fires and consolidated C in the form of iron-humus pans and concretions.

Another major pool of C, which should not be forgotten, consists of forest products (timber, pulp products, non timber forest products such as fruits and latex) and agricultural crops (food, fibre, forage, biofuels) taken off the site.

Table 3. Components of the terrestrial carbon pool (Ciais *et al.*, 2000).

C-INPUTS	C POOLS / Location	ORGANIC: LIVE — Biomass	ORGANIC: DEAD — Necromass	ORGANIC: DEAD — Humus	INORGANIC	C-OUTPUTS
Plant Assimilation	ABOVE-GROUND	Trees & other woody plants Leaves, fruits, twigs, branches & stems	Standing dead trees (snags) Above-ground coarse woody debris			Forest Product Agricultural crops CO_2 from decomposition
		Herbaceous plants	Litter Coarse woody debris			CO_2, CO, CH_4 from fires & other disturbances
	Forest Floor	Animals	Fine debris (leaves + twigs etc.)			CO_2, CH_4 from decomposition
Manure compost	SOIL Subsoil +Top soil	Living roots Fine Coarse	Dead roots Fine Coarse	Oa Horizon of Peat Soils Soil Organic Carbon (SOC) in mineral horizons Charcoal	Soil Inorganic C (SIC) Substances (Ca_2CO_3, etc.)	Particulate & dissolved OM Bicarbonates in water
Rain & other Inorganic Inputs	BELOW-GROUND	Soil Fauna Microbes		Carbon in Concretion		

3.1 Aboveground C: allometric relations for trees

A major proportion of the C and nutrients in terrestrial ecosystems is found in the tree component. To reduce the need for destructive sampling, biomass can be estimated from an easily measured property such as stem diameter at a specified height, by using an allometric equation. Such equations exist for many forest types and a small number are species specific. Destructive measurement of trees (cutting down and weighing) to generate allometric equations which have high precision needs a lot of labour and time, but when it is done it can be applied to other tree species in the same forest area. A substantial number of allometric equations have been developed for various climatic zones, forest types and tree species (Brown, 1997), using a variety of algebraic forms and parameter values. Anybody who wishes to use such an equation for a new situation is faced with a difficult choice among the various equations; the calculated estimates may vary by over a factor of 2 between equations which are applied to one specific data set (see also Ketterings et al., 2001). Collecting more empirical equations will hardly reduce this uncertainty for any new situation, unless we can better understand the background of the allometric equations in their link with the shape of trees.

Dead wood, both lying and standing, is an important C pool in forest that should be measured for an accurate representation of C stocks. We can assume fallen tree trunks are cylinders, and estimate their volume from measurements of their diameter and length. However, to estimate their biomass from their calculated volume, we need to take some samples, to measure the wood density. This is because the dead wood left in the forest is sometimes still solid, but is often found partly decayed.

3.2 Below ground C: root biomass

Roots are an important part of the C cycle because they transfer large amounts of C directly into the soil, where it may be stored for a long time. Most of the below-ground biomass of forest is contained in coarse roots (> 2 mm diameter), but most of that of annual crops is allocated to fine roots. Similar to the approach for aboveground biomass via allometric relations based on stem diameter, the belowground biomass can be estimated from the proximal roots at the stem base. The theoretical basis for this relationship is found in the fractal branching properties of root systems (van Noordwijk and Purnomosidhi, 1995).

3.3 Belowground C: Soil Organic Matter (SOM)

Soil organic matter content at any point in time is the result of the history of organic inputs and the past rates of decomposition, as determined by inherent properties of the soil and the vegetation or land use system of the site. There are large differences in C storage capacity of soil, related to

- soil texture (clay and silt content determine the amount of C that can be physically protected from decomposers, because it is located or ‘locked up’ in soil aggregates),
- landscape position and degree of drainage (peat and wetland soil conditions slow down decomposition considerably),
- mineralogy (young volcanic soils have a much higher C storage potential) and
- physical disturbance (soil tillage speeds up decomposition) (Van Noordwijk *et al.*, 1997).

Due to the large inherent variability of soil C content and the relatively slow responses to change (of the order of 10 years) it is not easy to assess the influence of land use or changes in land use on soil C stocks from 'survey' type data, especially where land use practices tend to occur on specific soils or landscape positions.

Current methods for inventory of soil C stocks at national scale (Houghton, 1997; Paustian et al., 1997) are based on an estimate of the soil C stocks under natural vegetation and the relative changes due to aspects of human land use. These include soil tillage, drainage and a reduction in organic inputs relative to the natural vegetation. Box 11 shows an example of how an estimate of soil C under natural vegetation (i.e. the potential C storage) may be obtained.

Box 11. Estimating a reference soil C value for potential C storage

Forest soils may lose a considerable part of their soil organic matter content after changes in management or conversion to other land use. Yet, the variation in soil organic matter content between different sites and soils is so large, that it is not easy to find a proper point of reference, to judge whether specific values are lower than would be expected under 'undisturbed' forest conditions. Therefore, van Noordwijk *et al.* (1997) developed an equation (using a very large data set from a national soil survey) that can be used to estimate the soil C content (C_{ref}) of a forest soil in Sumatra, on the basis of its texture and pH. When we combine it with the effects of sampling depth, we obtain:

$C_{ref(adjusted)} = (Z_{sample}/ 7.5)^{-0.42}$ exp(1.333 + 0.00994 * %Clay + 0.00699 * %Silt - 0.156 * pH_{KCl} + 0.000427 * Elevation + 0.834 (if soil is Andisol) + 0.363 (for swamp forest on wetland soils)

Where Z_{sample} is the sampling depth in cm, and elevation is measured in m above sea level.

The elevation term in the equation corrects for the decrease in average temperature when one moves up into the mountains. NB This equation applies to mineral upland soils. For young volcanic soils as well as wetland soils, a different equation should be used (van Noordwijk *et al.*, 1997).

Estimates of the C storage potential of soils can be derived from large data sets obtained in the soil surveys that have already been carried out in many tropical countries (Box 11) and/or by the use of simulation models that have been validated against such data sets elsewhere. For example, the impact of clay content on the reference C content of forest soils in Sumatra agrees with predictions of the CENTURY model (van Noordwijk et al., 2000). Many of the existing data sets in tropical countries have not been analysed to their full potential and thus could be used to obtain location-specific estimates of the reference C content.

The difference between current and potential C storage can then be expressed as a C saturation deficit (Van Noordwijk et al., 1997, 1998; Box 12).

The change (positive or negative) in soil C stocks that can be linked to management of the land is generally less than 20 Mg C ha^{-1}. This amount is smaller than the changes that can be achieved in aboveground C storage when woody vegetation is reintroduced or the typical lifespan of trees in the system is increased. This assessment, however, may change if more knowledge is obtained on C storage in deeper layers of the soil and the way this C storage depends on vegetation or land use.

Box 12. C saturation deficit

For any specific soil, we can now calculate a 'Carbon saturation deficit' on the basis of the difference between the actual soil C content and the amount that would be expected for a forest soil, with a long history of large litter inputs, for the same type of soil.

$$C_{satDeficit} = (C_{ref} - C_{org}) / C_{ref} \quad = 1 - C_{org} / C_{ref}$$

Where,
C_{org}/C_{ref} = soil organic carbon content relative to that for forest soils of the same texture and pH,
C_{ref} = a reference soil C level representative of forest soil.

3.4 Soil carbon distribution with depth

Soil C contents generally decrease with depth, as organic inputs are primarily deposited on the soil surface or occur in the topsoil where most of the turnover of fine roots occurs. In general, however, decomposition processes are slower at depth and the C on stocks that do exist below the topsoil are better protected from physical disturbance by soil tillage and they are thus likely to change more slowly after land use change. Yet, the potential for C storage in subsoil greatly exceeds that in the shallow topsoil layers, even if current C stocks are similar. Due to the large inherent variability of C contents, however, the assessment of land use change impacts on deep soil C storage is difficult, unless well-designed experiments are followed for a sufficiently long time period.

Soil depth varies considerably between sites, and so does the depth of the root system of trees that may be the source of most soil C storage at depth (besides the gradual downward transport of soluble organic compounds). Rooting depth of trees is related to the length and severity of the dry season, and within the humid tropics considerable variation between conditions is likely to exist - but has been poorly described so far, due to the difficulties of this type of research.

The distribution of soil C distribution with depth was, however, studied in Indonesia. Soil C data were collected throughout Jambi province (including the ASB benchmark areas) as part of the national soil survey, by the Indonesian Centre of Soil and Agroclimate Research (CSAR, Bogor), between 1981 and 1993 (Figure 10). The survey recognised 14 soil types under about 10 land cover types at 14 sites in 4 regencies. Some peat soils under swamp, natural forest and cleared natural forest have organic carbon contents of up to 40% or more, but most soils have a soil organic content of <7% C in the top layer.

Within the data the distinction between 'peat' and 'non-peat' is clear at the level of a soil layer, but not at the level of a soil profile: peat layers can occur in any thickness, and the soil classification system has to use an arbitrary boundary for its definition. The result is that some soils marked as 'peat' on a soil map have a considerable mineral layer of soil on top, other 'mineral' soils actually contain considerable amounts of soil C as peat.

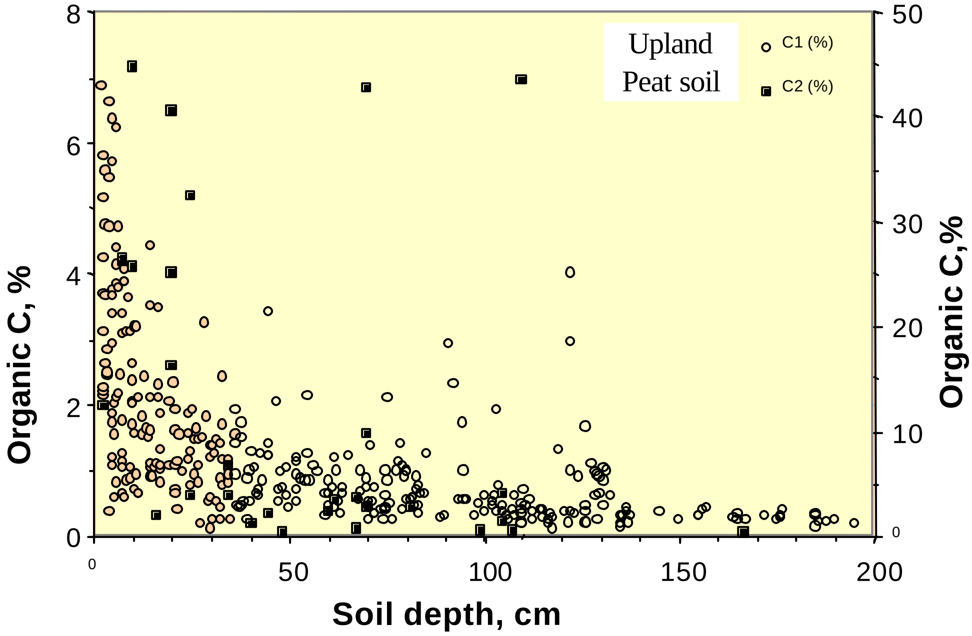


Figure 11A. Relationship between organic carbon (C_{org}) content of soils and depth for upland (circles, left hand scale) and peat (squares, right hand scale) soils, with various thickness of peat layers; data for Jambi province (central Sumatra) collected as part of national soil survey and analysed by Hairiah and Sitompul (2000).

If we ignore all soil layers that are 'peat', we find a considerable scatter of soil C data, but a general decrease of soil organic carbon content (C_{org}) with depth is evident amidst this variation (Figure 10B). We can fit an equation of the type:

$C_{org} = a\ Z^b$ where Z is depth and a and b (0.42) are constants.

We can use this equation to estimate the percentage of the soil carbon that occurs within a given depth of soil. If we know the average soil depth (i.e. where 100% of the soil carbon occurs) we can calculate a value for a, if we take the value of b to be 0.42. Thus, we can derive that if soils have an average depth of 2.5 m, 35% or 51% of their soil C will be stored in the top 20 or top 50 cm, respectively. If the average soil depth is 1.5 m, than 43 and 63% of soil C would be in the top 20 and top 50 cm, respectively.

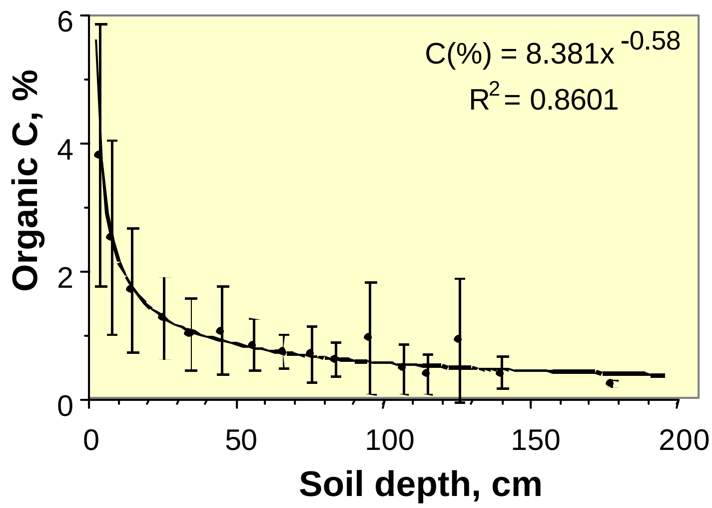


Figure 11.B. As for figure A, but focussing on the upland soils and indicating the range of individual observations for any depth

3.5 Peat soils

Peat soils cover a small fraction of the tropical forest area, but their C stock per unit area are so much higher than those of upland soils, that their total C storage may be equal to that of all upland soils in total. Concerns over reduction of the C release into the atmosphere should therefore lead to a reconsideration of any plans for ‘reclamation’ or agricultural use of these soils (Van Noordwijk et al., 1997).

The filled squares in Fig 11A (peat soils) show that there is much variation in the depth of the peat layer, and hence the C stock of these soils. In view of the total C stocks concerned, a better representation of these peat soils should become a top priority, as they are clearly susceptible to impacts of land use change. For example, for oil palm plantations on peat soils in Malaysia a subsidence of 2.5 cm per year was reported, half of which was attributed to compaction, half to decomposition/respiration. The latter translates to a C loss to the atmosphere of 10 - 20 Mg C ha^{-1} $year^{-1}$, which is 10 times greater than the losses on upland soils after forest conversion.

3.6 Case study: time-averaged C stocks in Brazil, Cameroon and Indonesia

Carbon stocks in a total of 93 forests or other land-uses established following slash and burn clearing were measured in the ASB project’s benchmark sites in Brazil (Pedro Peixoto and Theobroma), Cameroon (Yaoundé, M’balmayo, and Ebolowa), and Indonesia (Lampung and Jambi) (Woomer and Palm, 1998; Woomer et al., 2000). The land-uses sampled at each site represented a time course, or chronosequence, of land-use change. The measured C stock can be used to calculate time-averaged C; results are presented in Box 13.

3.7 Segregated or integrated landscapes for maximising C stocks?

The ‘segregate-integrate’ debate was introduced in lecture note 1: to attain the twin goals of productivity (food, timber, other products/raw materials etc.) and maintenance of environmental services (watershed functions, C stocks, biodiversity, etc.) what is the best spatial arrangement of land uses in the landscape? Would a fully segregated landscape, where natural undisturbed forests are kept separate from lands where intensive high-input agriculture is practised, be most efficient at achieving the two goals (Figure 13)? Or would a fully integrated landscape, composed entirely of a mosaic of crops, trees and small forest patches be best?

From a global warming perspective, we may come back to the issue of whether segregation of forests and agriculture, or an integration of forest functions and trees with agriculture is to be preferred. In a segregated landscape forests can be maintained (in theory at least) with their high C stocks and a forest soil that oxidizes some of the methane produced in the intensively used agricultural landscape, with its rice paddies and fertilized soil. In the integrated landscape, trees that provide useful products will also maintain reasonable time-averaged C stocks, but considerably less than the untouched natural forest, or even than forests under a sustainable, selective logging schedule.

Box 13. Measurement of C-stocks and time-averaged C of different land use types

Carbon losses and potential C sequestration with the various land-use transitions can be obtained by combining information on the aboveground time-averaged C and the relative soil C values for the different land-use systems (Appendix 1, Figure 12). The C losses from converting the natural forests to logged forests ranges from a low of 80 t C ha^{-1} to a high of 200 t C ha^{-1}. The majority of the C is lost from the vegetation with little loss from the soil. If the logged forests are further converted to continuous cropping or pasture systems, an additional 90 to 200 t C ha^{-1} are lost aboveground and 25 t C ha^{-1} are lost from the topsoil. Losses on conversion of logged forests to other tree-based systems would be less, from 40 to 180 t C ha^{-1} aboveground and 10 t C ha^{-1} from the soil.

If croplands and pastures were rehabilitated through conversion to tree-based systems, then this would result in net carbon sequestration. The amount of C that could be sequestered would range from 5 to 60 t C ha^{-1} above ground and 5 to 15 t C ha^{-1} in the topsoil over a 25 year period. The main point is that the potential for C sequestration in the humid tropics is above ground, not in the soil.

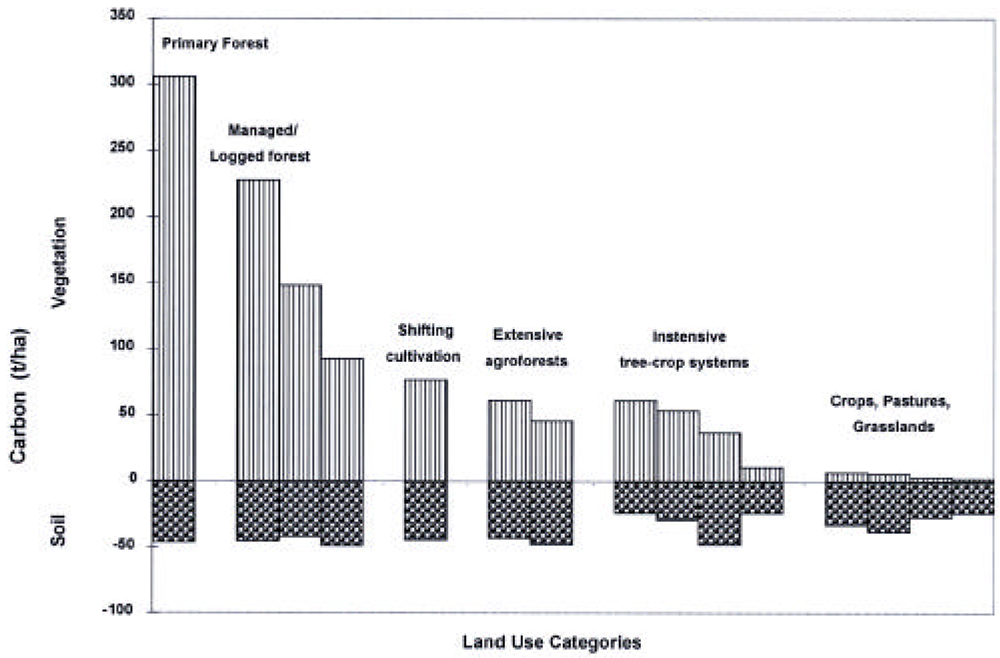


Figure 12. Above-ground time-averaged carbon stocks and total soil C (0-20 cm) for land uses in benchmark sites in Indonesia, Cameroon and Brazil.

The Segregate-Integrate debate can be treated in a simple and quantitative way where C stocks are involved (Table 4). The total C stock for the segregated landscape is

$$C_{segregated} = F_f\, C_{forest} + (1-F_f)\, C_{agriculture}$$

where F_f is the fraction of forest.

By solving for F_f in the equation

$$F_f\, C_{forest} + (1-F_f)\, C_{agriculture} = C_{integrated}$$

the break-even point may be found for C stocks in the types of landscape (Box 14), whereby

$C_{segregated} = C_{integrated}$

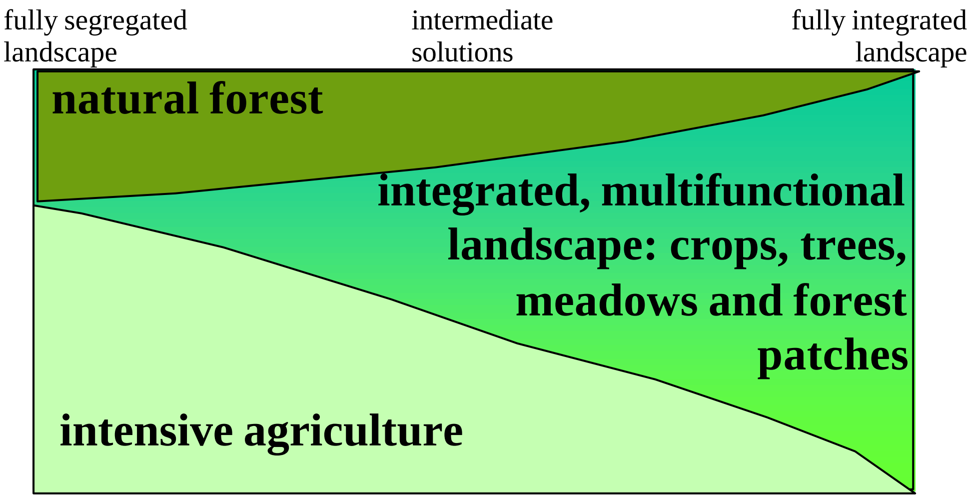


Figure 13. Segregated and integrated landscapes.

Table 4. Summarising C-stock conclusions for segregated or integrated landscapes.

Segregated - Agriculture	Segregated - Natural forest	Intermediate solutions	Integrated - Agroforestry mosaic
Aboveground C stocks less than 5 Mg C ha^{-1}, good soil management can restore up to 20 Mg C ha^{-1}	C stocks high (100 - 350 Mg C ha^{-1})	If forest fraction > 26%, C stocks can be 25 - 100 Mg C ha^{-1}	C stocks medium (25-100 Mg C ha^{-1})

Box 14. Example: 'break-even' points for C stocks in segregated and integrated landscapes

$$F_f\, C_{forest} + (1-F_f)\, C_{agriculture} = C_{integrated}$$

$$F_f\, (C_{forest} - C_{agriculture}) + C_{agriculture} = C_{integrated}$$

$$F_f = \frac{C_{integrated} - C_{agriculture}}{C_{forest} - C_{agriculture}}$$

So, if $C_{integrated} = 100$ (values found in the ASB research)
$C_{agriculture} = 30$
$C_{forest} = 300$

Then $\mathbf{F}_f = \frac{100 - 30}{300 - 30} = \frac{70}{270} = \mathbf{0.26}$

For the humid tropics to which the ASB data apply a (natural, non-logged) forest fraction of approximately 26% in an otherwise agricultural landscape will have a similar time-averaged C stock to a landscape based on agroforests (Box 14). With more forest, the segregate option is superior, with less forest the 'integrate' option is superior. Of course, the 'integrate option' covers a range of land use systems, and more exact calculations can be made on the basis of the above if a specific form of 'integrate' is chosen.

If we bring the annual emissions of CO_2 and other gases into consideration, the negative effects of intensive agriculture (due to CO_2 production during fertilizer production, plus methane and nitrous oxide emissions) will make the 'segregation' option less attractive, if the 'integrated' option can maintain its (lower) productivity at lower emissions per unit product. Such a comparison, however, is as yet difficult to make.

4. Modelling C stocks

4.1. Why do we want to model C stocks?

The direct measurement of C stocks on a large scale is not practical using currently-available methods, i.e. weighing plant samples for annual plants and measuring specific parameters for trees (e.g. tree diameter, wood density etc.). In the case of trees, only the C stocks of aboveground parts can be estimated with the allometric method (section 3.1). The estimation of regional C stocks by extrapolating from point data to large areas would be inaccurate in some regions due to variability in plant species and ecological factors (such as climatic and edaphic factors).

The application of a suitable model is an alternative way to solve these problems. The 'CENTURY' model (Parton et al., 1987 and 1988; Metherell et al., 1993) is one of the models available that can be used to assess plant biomass and soil organic matter for a range of land use practices. This model has been successfully applied in different parts of the world, including tropical areas (Parton et al., 1987, 1988 and 1994; Woomer, 1993).

4.2 The CENTURY Model: simulating land use change

The CENTURY model contains six simulation submodels, relating to soil organic matter (SOM), nitrogen, phosphorus, sulphur, water budgets and plant production. As we are interested here in modelling carbon stocks of vegetation in various land cover types, the plant production submodel is described below.

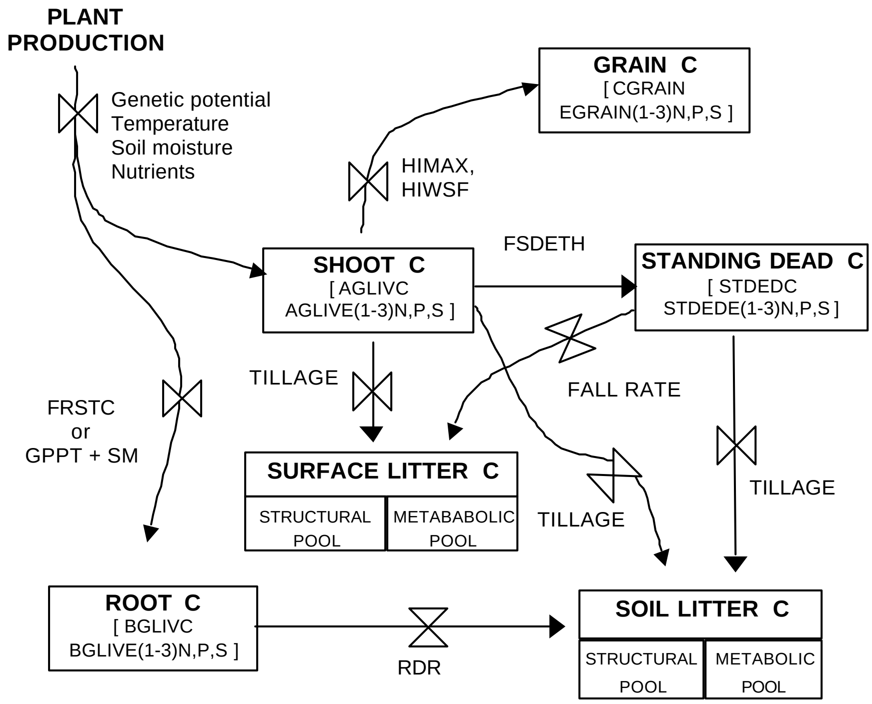
4.2.1 The plant production submodel – how it works, and what it assumes

CENTURY calculates the production of plant carbon within the plant production submodel using a simple approach that does not involve the complex physiological processes that determine plant growth and development. In principle, the input of carbon into the plant is first determined by the maximum rate of net photosynthesis, which in turn is dependent (mainly) upon:

- the photosynthetically active radiation (PAR)
- plant characteristics which control the interception of PAR
- efficiency of photosynthesis and the metabolic reactions that convert carbohydrate to plant biomass and maintain the standing biomass.

In the CENTURY model, the maximum potential production of carbon by the plant is used as an input parameter and specific values for every crop or vegetation type can be adjusted to the local environmental conditions. Generally, the maximum rates are in the range of 200 to 580 kg dry matter ha^{-1} day^{-1} corresponding to 240 to 700 g C m^{-2} month^{-1}. The seasonal variation in carbon production is calculated as a function of temperature rather than PAR. The actual production of carbon is obtained after corrections are made for water, temperature, shading and nutrients (**N, P** & **S**).

The net amount of carbon produced as described above can then 'flow' into plant parts such as shoots, grains and roots (e.g. Figure 14). Within the model, this process is controlled by parameters which can be used as inputs to the model. Thus, these parameters can be modified to provide a more accurate representation of the particular plant species being modelled. Over time the plants grow, grain may be harvested and the plants eventually die. The rate of shoot death is assumed to be 6% per 30 days, and this increases to 98% at plant senescence. The dead shoots are transferred to the 'standing-dead' compartment of the model (Figure 14), and are subsequently transferred to the 'surface litter' compartment at a rate of 10% per 20 days. Roots die at a rate of 4% per 30 days, and these are transferred directly into the soil litter pool (Figure 14).



KEY

FRSTC = Fraction Root Carbon
FSDETH = Shoot Death Rate
GPPT = Grow Season Precipitation
HIMAX = Harvest Index Maximum
HIWSF = Harvest Index Water Stress Factor
RDR = Root Death Rate
SM = Initial Soil Moisture

MODEL OUTPUT VARIABLES

CPRODA = Annual Total Production
AGCACC = Above Ground Growing Season Production
BGCACC = Below Ground Growing Season Production
[Other output variables are shown in parentheses.]

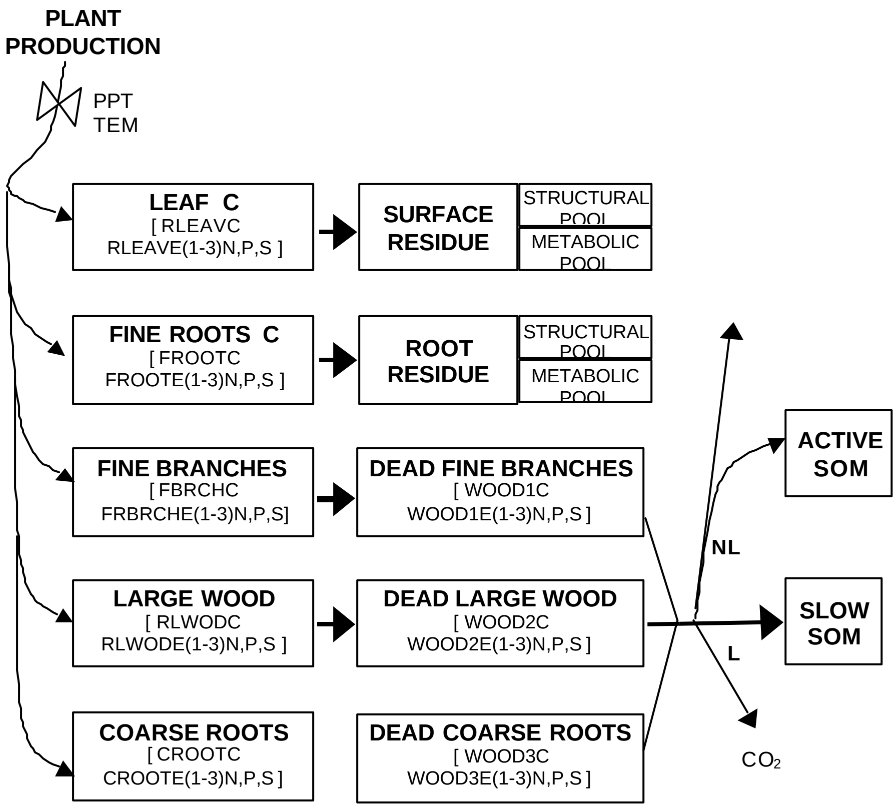
Figure 14. Flow diagram of carbon for the crop/grassland model within the CENTURY model: the arrows indicate flows of C and N between pools (boxes), the labels on the arrows indicate the main factors controlling the rates of the flows (see Key).

The generic 'plant' production submodel can be used to simulate many types of annual crops or grassland, but for trees and forest vegetation, some modifications are needed to account for woody tissue (Figure 15). The annual maximum production of aboveground (Pmax) and belowground (Rmax) biomass in the forest model is based on annual precipitation (APPT, in mm) as shown by the following equations.

Pmax = -40 + 0.77 APPT
Rmax = 100 + 0.70 APPT

The monthly maximum plant production during the growing season is obtained from the annual maximum production divided by the length of growing season. The availability of mineral N can control plant and forest production. When mineral N supply is insufficient to produce plant material with the desired C/N ratio, plant production is proportionally reduced.

The carbon produced by the plants/forest can be used in respiration by the plants themselves (and released in the form of CO_2) it can enter the soil or surface litter pools and eventually reaches the soil organic matter pools (via decomposition). Again, some C is released as CO_2, this time due to respiration by microbes. There may also be some leaching of soluble C. The three major soil organic matter pools, in increasing order of stability and resistance to decomposition, are the ‘active’, ‘slow’ and ‘passive’ pools. Thus the model is dynamic, calculating the carbon stocks of a system over time, in terms of above and belowground carbon, including that stored in the soil.



KEY

L = Lignin
NL = Non-Lignin
PPT = Monthly Precipitation
TEM = Monthly Soil Temperature
SOM = Soil Organic Matter

MODEL OUTPUT VARIABLES

CRTACC = Annual Coarse Wood Production
FBRACC = Annual Fine Branch Production
FRACC = Annual Total Tree Production
FROOTC = Annual Fine Root Production
RLVACC = Annual Leaf Production
RLWACC = Annual Large Wood Production
SUMRSP = Monthly Maintenance Respiration

[Other output variables are shown in parentheses.]

Figure 15. Flow diagram of carbon for the forest production model within the CENTURY model: the arrows indicate flows of C and N between the various organic pools (boxes), the labels on the arrows indicate the main factors controlling the rates of the flows (see Key).

4.2.2 Results of simulations of the CENTURY model

A valuable application of the CENTURY model is in assessing the effects of land use change on C stocks, as this is the major process causing substantial losses of C from the terrestrial C pool. In Jambi province in Indonesia, for instance, huge areas of primary forest have been converted into other land use types causing substantial reductions in terrestrial C stocks (Murdiyarso and Wasrin, 1995). If we can model this process we can thus gain a better understanding of the relations between terrestrial C stocks and land use changes at a global scale.

- The CENTURY model was used to predict C stocks (aboveground vegetation and soil organic carbon) in forest and forest converted to **rubber** in Jambi, Indonesia and to **cacao** in Cameroon, as a case study. The climate and soil characteristics in both study sites (countries) are different (Table 5). Precipitation is higher in Indonesia (2.94 m year^{-1}) than in Cameroon (2.06 m year^{-1}), and temperature is also higher in the former than in the latter site. The average minimum daily temperatures are 26.0 and 17.6 ^{o}C in Indonesia and Cameroon, respectively, and the average maximum daily temperatures are 31.8 and 30.9 ^{o}C, respectively.

Table 5. The geographical location and selected soil characteristics of Jambi, Indonesia and Ebolowa, Cameroon

Sites	Latitude	Longitude	pH	Sand	Silt	Clay	Bulk Density
Jambi, Indonesia	4.00	104	4.75	0.462	0.244	0.294	1.1
Ebolowa, Cameroon	5.45	76	5.40	0.54	0.36	0.10	1.4

Natural forest

- The accumulation of carbon in the **aboveground** parts of forest trees increases rapidly in the first 200 years, is slower thereafter and has become relatively constant by the year 1000 of the simulation (Figure 16a). In years 300 and 1000, the predicted C of aboveground parts in Jambi is about 300 and 470 Mg C ha^{-1} respectively. This is close to the values for aboveground C derived from field measurements in forest in Rantau Pandan (264 Mg C ha^{-1})[1] and at Pasir Mayang (421 Mg C ha^{-1}). Forest in Cameroon has a lower capacity to accumulate C and has produced only about 210 and 370 Mg C ha^{-1} by years 300 and 1000 respectively.
- The predicted accumulation of C in the **soil** during the growth of forest increases continuously, but its rate of increase declines gradually with time, with a pattern similar to that shown by the aboveground parts (Figure 16b). In years 500 and 600, the total soil C content in Jambi reaches 72 and 80 Mg C ha^{-1} respectively and this corresponds with a C_{org} of 3.28 and 3.65% (for the top 20 cm of a dry soil where bulk density is 1.1 mg cm^{-3}). These predicted values are extremely close to actual values measured in Jambi at Rantau Pandan (71 Mg C ha^{-1}) and at Pasir Mayang (79 Mg C ha^{-1}). In Cameroon, the accumulation of soil C is lower and is still less than 50 Mg C ha^{-1} (a C_{org} value of 1.75%) in year 500.

[1] This figure was derived from measurements of tree diameter at breast height (DBH) in the field, which were then converted into an estimate of tree biomass using the allometric equation $Y = 0.0661\ D^{2.59}$, where Y = biomass (kg) and D = Diameter at breast height (DBH). This gave biomass figures of 587 Mg ha^{-1} and 936 Mg ha^{-1} at Rantau Pandan and Pasir Mayang respectively. Tree biomass was converted into mass of C by multiplying by the average % C content (45 %), giving 264 Mg C ha^{-1} at Rantau Pandan and 421 Mg C ha^{-1} at Pasir Mayang.

Forest conversion to rubber or cacao

- Simulated conversion of forest in Indonesia, by clearing and burning after logging, to rubber grown in mixture with rice in the first two years caused a substantial reduction in the C accumulation in aboveground parts (Figure 17a). For 20 year old rubber (around year 365 of the simulation) C stocks simulated by the model are close to the average value of four aboveground C estimates (Figure 17a) which were obtained using the allometric method (i.e. 40 Mg C ha^{-1} at Rantau Pandan and 78-94 Mg C ha^{-1} at Bungo Tebo). In the same figure, the observed aboveground C stocks in rubber plantations in Malaysia (Shorrocks *et al.*, 1965) correspond closely with the model outputs for the first 6 years and at 24 years after planting, but were higher than that predicted by the model in the 10^{th} year.

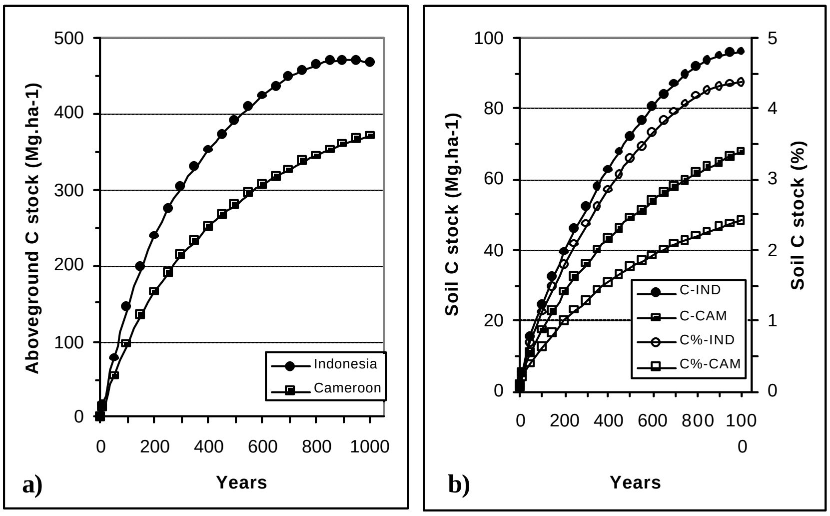


Figure 16. Accumulation of C with time in (a) aboveground parts of forest and (b) in the soil in Jambi, Indonesia, and Ebolowa, Cameroon (results of a simulation using the CENTURY model).

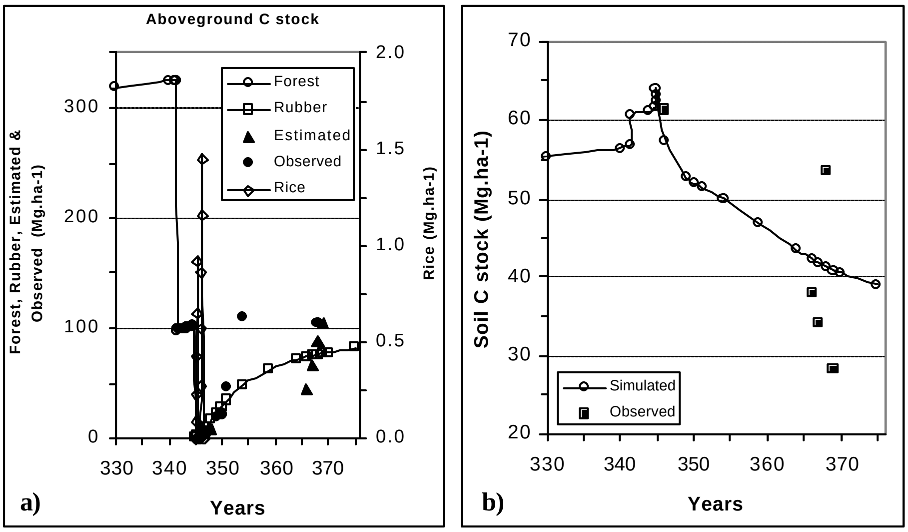


Figure 17. Accumulation of C in (a) aboveground parts and (b) in the soil, for rubber planted after rice for two years following the removal of natural forest (results of a simulation using the CENTURY model where clearing of forest occurs at year 340 of the simulation). Open symbols represent values simulated by the model; 'Estimated' refers to C stock estimates obtained using allometric equations and field-measured tree diameters in Jambi, Indonesia; 'Observed' values are from (a) rubber plantations in Malaysia (Shorrocks *et al.,* 1965) and (b) Jambi, Indonesia.

- In a simulation for Cameroon, cacao grown after *Chromolaena* sp. (2 years) following forest removal was estimated to produce about 70 Mg C ha^{-1} after 25 years (Figure 18a) which is slightly lower than that observed in the field (88.72 Mg C ha^{-1}).
- The model predicted that soil C content declines when forest was replaced by rubber in Indonesia or cacao in Cameroon, and the rate of decrease was faster under rubber (from 55 to 40 Mg C ha^{-1}, Figure 17b) than under cacao (from 38 to 31 Mg C ha^{-1}, Figure 18b). Under rubber in Indonesia, the predicted soil C content after 25 years lies within the range observed at Bungo Tebo (35-67 Mg C ha^{-1}, Figure 17b).

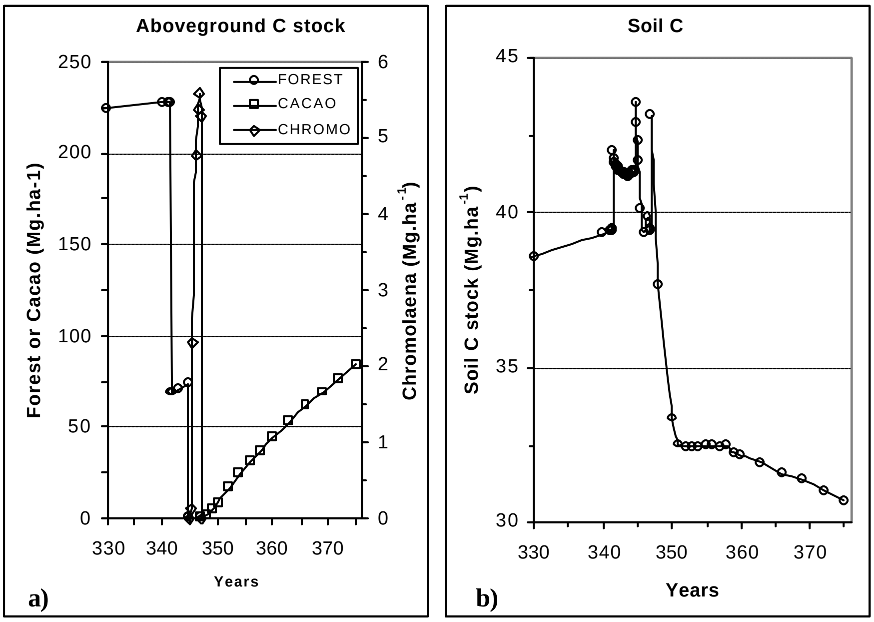


Figure 18. Accumulation of C in (a) aboveground parts and (b) in the soil, for cacao planted after *Chromolaena* sp. for two years following the removal of natural forest (results of a simulation using the CENTURY model where clearing of forest occurs at year 340 of the simulation).

5. International policies on carbon, greenhouse gases and 'clean development'

In 1992 the UN Framework Convention on Climate Change (UNFCCC) was signed by the heads of state attending the UN Conference on Environment and Development in Rio de Janeiro. In January 1997 the convention became ratified by 165 nations and thus became legally binding in an international sense. In Article 2 the convention states that its ultimate objective is to achieve:

> "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

The convention was certainly a breakthrough in gaining recognition for the risks of climate change as a consequence of greenhouse gas emissions, but the wording of the convention reflects a diplomatic compromise rather than a clear set of rules. In a number of follow up meetings ('conventions of parties' or CoP) further specification of such rules has been attempted. Of specific relevance here is the Kyoto Protocol of 1997 where the developed countries (the 'Annex I Parties') agreed to limit and reduce their emissions of greenhouse gases between 2008 and 2012. This protocol has not yet been ratified by countries responsible for the majority of current emissions, and is thus not yet legally binding.

The Kyoto Protocol made a provision for Land Use, Land-Use Change and Forestry ('LULUCF') activities to be taken into account in the assessment. More specific consequences of these LULUCF activities have since been subject to much debate (Watson *et al*., 2000). There are still widely different views on the relevance and practicability of including such activities in the way commitments on overall reductions of greenhouse gas emissions can be met (see the exercise below).

The '**Clean Development Mechanism' (CDM**) was created as part of the Kyoto Protocol in 1997 :

- to lower the overall cost of reducing greenhouse gas (GHG) emissions released to the atmosphere, and
- to support sustainable development initiatives within developing countries
- (WRI, 2001).

The CDM allows Annex I (developed) countries to invest in GHG abatement activities in non-Annex I (developing) countries. Reductions in emissions (subject to certification) may then be credited against the developed country's 2008-2012 targets, so reducing the cutbacks that would have to be made within that country's own borders. Of course, it doesn't matter exactly where in the world the GHG emissions are actually reduced, as the effect on the global climate will be the same.

In theory, developed countries would gain because abatement opportunities are less expensive in developing countries. Developing countries would also benefit, from increased investment flows and the CDM's requirement that sustainable development goals must also be addressed (WRI, 2001). Furthermore, activities under the CDM would also provide a source of capital for financing clean, energy-efficient economic development and for projects with the potential to reduce deforestation and forest degradation in developing countries. In practice, however, concrete guidelines for implementing the CDM are still being negotiated.

Exercise
Read and discuss the following articles. The first was written at the time of the November 2000 convention of parties in the Climate Convention ('CoP6' in The Hague, the Netherlands) where an attempt to get more binding agreements failed; the second in July 2001, at the time of CoP7 in Bonn, Germany.

1) Emissions credits: Case for trees isn't clear-cut

"The role of trees in reducing greenhouse gas emissions has come under question and will be debated at the global warming conference in The Hague"

November 13, 2000; Web posted at 21:17 GMT by Environmental News Network staff on http://www4.cnn.com/2000/NATURE/11/13/forest.emissions.enn/.

The global solution to combat climate change is far from being clear-cut. As 180 nations gather to finalise a global climate change treaty in The Hague, Netherlands, in the next two weeks, a controversial question will accompany them: Should forests be used - and credited - for reducing greenhouse gas emissions by absorbing carbon dioxide? As mandated by the Kyoto Protocol in 1997, industrial nations are required to reduce carbon emissions by 5 percent below their 1990 levels between 2008 and 2012. The United States, Japan, Australia and Canada are proposing to curb their rapidly growing emissions from energy use by applying forest carbon storage to meet Kyoto Protocol targets.

Led by Worldwide Fund for Nature (WWF), the Native Forest Network and Greenpeace, a coalition of conservation groups claim that industrial nations should not be allowed to apply credit for carbon that is stored in trees. Counting on forest carbon storage to meet Kyoto Protocol targets does not follow the intent of the agreement, the groups claim, and it will lead to rapid deforestation. "(As currently drafted) the Kyoto Protocol could actually accelerate forest destruction by giving incentives to plant large-scale plantations on formerly native forest land," said Jennifer Morgan, climate change campaign director for WWF.

A report released Thursday by the three organisations points to several studies in Australia, where carbon sequestration projects led to deforestation and the loss of biodiversity. The native forest in Tasmania is being replaced with eucalyptus plantations that grow faster. Pictured here, Porter Bridge Road in Tasmania. The report blames Japan's largest power utility, the Tokyo Electric Power Company, for destroying native forest in the Australian state of Tasmania and replacing it with fast-growing eucalyptus plantations intended for carbon credits under the Kyoto Protocol. The company's investment of US$5 million accounts for 3,000 hectares of eucalyptus tree plantations that are expected to yield TEPCO 130,000 metric tons of carbon credits. These credits could be used to offset rising carbon emissions in Japan. "This project in Australia is just one example of what could go terribly wrong for the world's forests if the governments of Japan, Australia and the United States get their way next week at the climate summit in the Hague," Morgan said. "Instead of reducing the pollution that causes global warming, these countries are looking for quick fixes that have high risks for forests." According to the American Lands Alliance, agreements made at the climate change summit in The Hague could affect the future management of 500 million acres of forest land in the United States. "A good treaty has the potential to allow landowners to protect their property and receive carbon credits," said American Lands Campaign director Steve Holmer. "The problem is that the way the treaty is written now, carbon credits could go to timber companies that log old growth and replace them with genetically engineered tree farms." "In developing countries the situation could be even worse because developing countries do not have to count their emissions under the Kyoto Protocol," Morgan notes. "Private companies from industrialized nations will seek cheap carbon credits for their country in the developing world."

WWF and Greenpeace are calling on the Hague convention to exclude reliance on carbon sinks from the Kyoto Protocol and its Clean Development Mechanism. Industrialized nations should instead achieve their Kyoto commitments through domestic reductions in global warming gases and energy conservation programs, they say. A study published in Thursday's issue of the journal Nature supports this argument.

Forests might actually accelerate the process of global warming because carbon dioxide will be released from soils and decaying forests as the climate warms, researchers at the United Kingdom's Hadley Centre for Climate Prediction noted. "Trees only absorb carbon to a certain point in their lifetime," Morgan said. They have a saturation limit, like everything else." "Warmer temperatures and less precipitation can also have a severe impact on forests," she explained. "In a quicker period of time it could turn a forest from a sink where it is absorbing carbon into a carbon source. If we are trying to meet the (Kyoto) target through forest activity and sink activity, which are inherently risky and impermanent, then you are putting in place a very ineffective way to fight global warming."

2) Carbon sinks 'little help to climate'

By BBC News Online's environment correspondent Alex Kirby

Source: BBC News Online
http://news.bbc.co.uk/hi/english/sci/tech/newsid_1426000/1426453.stm

Sunday, 8 July, 2001, 23:34 GMT 00:34 UK

Scientists say relying on trees and vegetation to absorb carbon dioxide (CO_2) will do little to tackle global warming. They say the amount of carbon these "sinks" can store is far less than the quantities emitted by burning fossil fuels.

Some countries want to use sinks extensively to meet their commitments under the Kyoto Protocol on climate change. But the scientists say there is really no alternative to actual emission cuts.

In a report published by the UK's science academy, the Royal Society, they say sinks cannot be a long-term substitute for emissions cuts.

They say governments meeting on 19 July in the German city of Bonn to negotiate the protocol's detailed working should not rely too heavily on forests and farmlands to soak up CO_2.

Rather the report suggests countries should focus on restructuring the generation and use of energy, and on technological innovations such as improved fuel efficiency and technology transfer to the developing world.

Ultimate solution

The chairman of the working group that prepared the report is Professor David Read.

He said: "These measures may be socially and politically more painful to implement than land carbon sinks.

"But they must provide the ultimate solution to the problem of reducing the amounts of greenhouse gases in the atmosphere."

The report focuses on terrestrial sinks - although it is possible to store CO_2 in the oceans, land sinks are the only ones dealt with under Kyoto.

Professor Read said: "We do not fully understand the processes that control how much CO_2 is absorbed by vegetation and soils acting as sinks.

"And we need more reliable methods of quantifying and verifying their contribution towards targets set by the protocol.

"They may help to reduce greenhouse gas levels in the atmosphere during the short term.

"But the amounts of CO_2 that can be stored are small compared with emissions from the burning of fossil fuels."

Land-based vegetation and soils currently absorb about 40% of global CO_2 emissions from human activities.

The report recommends that the capacity of these sinks should be increased. It warns that changes in farming and forestry, like the widespread use of nitrogen-based fertilisers, can be problematic.

While they are intended to increase the amount of CO_2 absorbed by sinks, it says, they may actually increase climate change by releasing other greenhouse gases, like methane and nitrous oxide.

'Bit of a sideshow'

The report says the maximum contribution from such changes, and from slowing deforestation, is modest.

It estimates it at a quarter of the emissions cuts needed by 2050 to avoid large increases in global average temperatures.

Professor John Shepherd, a member of the working party, told BBC News Online: "Sinks are really a bit of a sideshow to the main event.

"It would be better to spend less time worrying about them and look instead at the real long-term problems.

"The size of the potential sinks is quite modest, and they'd all be used up in a few decades.

"And they're not very stable. If you chop down the trees you release the carbon, and if you convert the land to wetland you release methane.

Carbon emitters

"Global warming itself may turn them from sinks to sources of carbon.

"Rising temperatures will make the bacteria more active, and they'll break down the carbon faster."

Talks last November on finalising the protocol broke down, partly over disagreements on sinks.

Japan is leading calls in Bonn for sinks to be widely exploited. It wants to meet almost 60% of its cuts in this way.

III. Reading Materials

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Appendix 1. Carbon sequestered (- t C ha^{-1}) or lost (+) from converting from one land-use system to another. (See also Box 13)

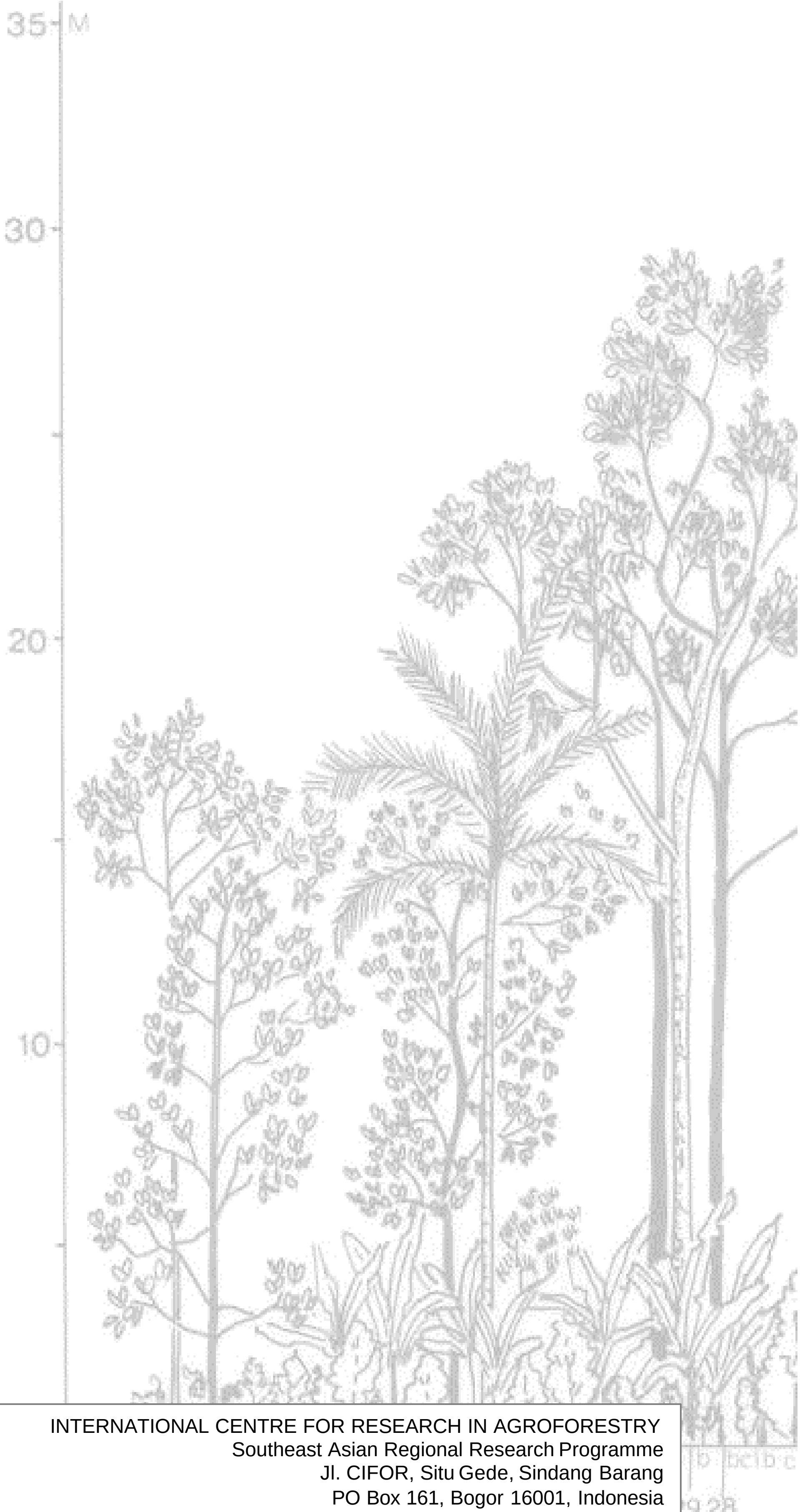
INDONESIA	**Primary forest**	**Logged Forest**	**Jungle Rubber** (permanent)*	**Jungle Rubber** (rotational)	**Oil Palm**	**Pulp Plantation**	**Crop/ Imperata**
Time-averaged C (t C ha^{-1})	306	93	89	46	54	37	2
	Carbon lost (+) or sequestered (-) during conversion from land use in column to land use in row						
Logged Forest	213	0	-4	-47	-39	*-56*	*-91*
Jungle Rubber (permanent)*	217	4	0	-43	-35	-52	-87
Jungle Rubber (rotation)	260	47	-43	0	8	-9	-44
Oil Palm	252	39	-35	-8	0	-17	-52
Pulp Plantation	269	56	-52	9	17	0	-35
Crop/Imperata	304	91	-87	44	52	35	0

CAMEROON	**Logged Forest**	**Shifting cultivation**	**Jungle Cacao** (permanent)	**Jungle Cacao** (rotational)	**Oil Palm**	**Crop/ bush fallow**	**Crop/ Chromolaena**
Time-averaged C (t C ha^{-1})	228	77	89	61	36	38	6
	Carbon lost (+) or sequestered (-)during conversion from land use in column to land use in row						
Forest	0	-151	-139	-167	-192	-190	-222
Shifting cultivation	151	0	12	-16	-41	-39	-71
Jungle Cacao (permanent)	139	-12	0	-28	-53	-51	-83
Jungle Cacao (rotational)	167	16	28	0	-25	-23	-55
Oil Palm	192	41	53	25	0	2	-30
Crop/Bush fallow	190	39	51	23	-2	0	-32
Crop/Chromolaena	222	71	83	55	30	32	0

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

* System based on gap-replanting, not on slash-and-burn at a whole field level

Contents of this series of lecture notes



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INTERNATIONAL CENTRE FOR RESEARCH IN AGROFORESTRY
Southeast Asian Regional Research Programme
Jl. CIFOR, Situ Gede, Sindang Barang
PO Box 161, Bogor 16001, Indonesia
Tel: +62 251 625415, fax: +62 251 625416, email: icraf-indonesia@cgiar.org
Web site: http://www.icraf.cgiar.org/sea