TROPICAL FORESTRY PRACTICES FOR CARBON SEQUESTRATION[1]

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ABSTRACT

Carbon sequestration through forestry has the potential to play a significant role in ameliorating global environmental problems such as atmospheric accumulation of GHG's and climate change. This chapter provides an overview of various aspects related to carbon sequestration through forestry. It describes the main concepts of carbon fixation; the trends in global environmental policy are discussed; different forestry practices are listed; examples of existing projects are given; and finally, a case study of a carbon sequestration project in Malaysia is described. The paper also discusses issues related to the quantification of carbon sequestration potential of different forestry options. This section was included with the intention of specifically highlighting some problems related to commercial transactions for carbon sequestration.

Key words: carbon sequestration, CO_2 offset, tropical forestry, dipterocarps.

INTRODUCTION

Concern about rising atmospheric concentrations of greenhouse gases [Wigley 1993] has prompted the search for methods of sequestering carbon in plant biomass. Due to cost effectiveness, high potential rates of carbon uptake, and associated environmental and social benefits, much attention has focused on promoting tropical forestry for offsetting carbon emissions [*e.g.* IPCC 1992].

This chapter has been written to provide an overview of various aspects related to carbon sequestration through forestry. It describes the main concepts of carbon fixation; the trends in global environmental policy are discussed; different forestry practices are listed; examples of existing projects are given; and finally, a case study of a carbon sequestration project in Malaysia is described. The paper also discusses issues related to the quantification of carbon sequestration potential of different

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[1] In: Dipterocarp Forest EcoSystems – Towards Sustainable Management. Schulte, A. & Schone, D. (Eds.). World Scientific, Singapore, 1996. Pp. 308-334.

forestry options. This section was included with the intention of specifically highlighting some problems related to commercial transactions for carbon sequestration. Although the concepts and ideas are generic and applicable to any forest type or part of the world, this chapter specifically addresses the issues related to dipterocarp rainforests in the South East Asia region.

BASIC CONCEPTS: BIOMASS AND CARBON

Carbon sequestration through forestry is based on two premises. First, that carbon dioxide is an atmospheric gas that circulates globally; consequently, efforts to remove greenhouse gases (GHG's) from the atmosphere will be equally effective whether they are based next door to the source or across the globe. Second, green plants take carbon dioxide gas out of the atmosphere in the process of photosynthesis and use it to make sugars and other organic compounds used for growth and metabolism. Long-lived woody plants store carbon in their wood and other tissues until they die and decompose at which time the carbon in their wood may be released to the atmosphere as carbon dioxide, carbon monoxide or methane, or it may be incorporated into the soil as organic matter [Anderson and Spencer 1991].

Plant tissues vary in their carbon content. Stems and fruits have more carbon per gram than do leaves, but because plants generally have some carbon-rich tissues and some carbon-poor tissues, an average concentration of 45-50 % carbon is generally accepted [Chan 1982]. Therefore, the amount of carbon stored in trees in a forest can be calculated if you know the amount of biomass or living plant tissue in the forest and apply a conversion factor.

When considering carbon storage, not all forests are equal. Generally, longer-lived, higher density trees store more carbon than short-lived, low density, fast-growing trees. This does not mean that carbon offsets which involve big, slow-growing trees are necessarily better than those involving plantations of fast-growing trees. What it does mean is that it is important to talk about various offset options with a time scale specified and decide whether the objective is to store carbon, prevent further carbon dioxide emissions or to actively remove carbon dioxide from the atmosphere.

INDUSTRY, FORESTRY AND THE CLIMATE CHANGE CONVENTION

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The signing by 153 nations at the 1992 UNCED Earth Summit of the Framework Convention on Climate Change [Grubb *et al.* 1993] is evidence of intent to restrain the build-up of GHG's in the atmosphere. The most important of these gases by weight is carbon dioxide [IPCC 1992], which is released principally by the combustion of fossil fuels, particularly coal and oil, by the burning or decay of vegetation and by flux with oceans. Although the loss and degradation of tropical forests probably contribute only about 30% of total net CO_2 emissions [Houghton *et al.* 1992], these habitats represent one of the most productive long-term carbon sinks. The central need to achieve a reduction in CO_2 levels is for reduction in fossil fuel consumption, which directly affects the industrial sector. While changes in national taxation and regulatory frameworks will be the main tools for change, another option is to allow the industry to "offset" some of their CO_2 emissions by funding improvements in tropical forest management that sequester an equivalent weight of carbon from the atmosphere [Jones and Stuart 1994, Rose and Tietenberg 1993, Pachauri and Soni 1994].

Although there are not any regulations yet forcing any country to offset their carbon emissions, there are emerging mechanisms which already provide enough incentive for companies to initiate carbon offset programs. The most advanced is the Section 1605-b of the US Energy Policy Act, which allows companies to register their voluntary activities related to GHG's mitigation in anticipation to an expected environmental tax legislation [Embree 1994, Jones and Stuart 1994]. The industrial sector which has been most actively involved in this initial stage of commercial carbon offset is the power generation industry. Electric power generation with its heavy reliance on coal, which is about 50-70 % carbon by weight, contributes about 30% of total CO_2 emissions [World Bank 1993] and in most countries this sector consists of a few large companies. Many companies have programs for reducing emissions based on fuel-switching, improvements in efficiency, and electricity or energy conservation (demand side management), while a few are already supporting projects for carbon offset through forestry.

One of the first initiatives on carbon sequestration through forestry was taken by Applied Energy Systems (AES), a US-based electrical power producer, in order to mitigate the CO_2 emissions of a new power plant in the US. Since 1990, AES has been partially funding a community-based agroforestry project in Guatemala together with CARE, an international development and relief organization [Faeth *et al.* 1994]. Because of the encouraging results of this project, AES commissioned the World Resource Institute (Washington DC) to search for other project possibilities to expand their carbon sequestration programme, and the most promising proposals are listed in the report compiled by Faeth *et al.* [1994]. One of the largest ongoing carbon offset programmes is the one created by the Face

(Forests Absorbing Carbon-dioxide Emissions) Foundation of the Netherlands, an organization set up by the Dutch Electricity Generating Board. Since 1992, Face initiated a series of projects in different countries in order to establish 150,000 ha of forests throughout the world, which was calculated as the area required to sequester a volume of CO_2 equivalent to the emissions of a medium size coal-burning power station during its life time [Dijk *et al.* 1994, Verweij 1994]. Another initiative with great potential was initiated by the New England Power Company of Boston (USA), which is funding a pilot project to introduce reduced impact logging techniques to prevent the unnecessary decomposition of trees damaged during harvest operations and therefore CO_2 emissions from decomposing biomass [Marsh 1992, 1993; Putz and Pinard 1993]. Other smaller carbon sequestration projects undertaken in Russia and the USA are described in Dixon *et al.* [1993a].

Carbon offsets in tropical forests by reduced carbon loss or by increased carbon sequestration, as in reduced impact logging or reforestation programs, are splendid examples of global sharing of the financial burden of conservation. From a climate-change perspective this is eminently reasonable because CO_2 and other heat-trapping gases circulate globally. From a political perspective carbon offset programs should be acceptable in the tropics and elsewhere because they provide a mechanism for motivating the wealthy countries of the world to pay for a benefit of forest conservation that transcends national borders. It promotes the transfer of funds from industrialised countries to tropical countries as a commercial transaction, as opposed to charity [Marsh 1992].

It must be mentioned here that forestry will never be a solution for all the environmental problems related to the accumulation of GHG's in the atmosphere. As pointed out by many countries during the Earth Summit, polluters should also attempt to reduce their emissions [Grubb *et al.* 1993]. However, there are enough areas under forest land or deforested that, if properly managed, could sequester up to 15 % of global emissions of carbon dioxide and other GHG's [IPCC 1992]. The acknowledgement of this idea may play a central role in improving the health and productivity of forests around the world.

Criteria for defining carbon offset

The need of industries to mitigate their carbon dioxide emissions is creating the business of carbon offsets through forestry. It is important, therefore, to define what exactly constitutes a true carbon offset.

What is carbon offset ? In this report it is defined as the result of any action specifically taken to remove from and/or prevent the release of carbon dioxide into the atmosphere in order to balance emissions taking place elsewhere. However, in the context of forestry and conservation practices, it should be recognised that not all forest areas can be considered as generating offsets. For example, existing national parks may not be considered to generate carbon offsets; these forests were already in existence when the concept of carbon sequestration arose. Therefore, simply renaming them as "carbon offsets" does not involve any active removal of CO_2 from the atmosphere. On the other hand, the establishment of new forests with the primary objective of carbon sequestration would not occur "but for" a deliberate intention. This may then be rightly considered as offsets. The idea is that "but for" our deliberate intervention in an area or its forestry practices such an offset would not occur. In a number of cases, it may be necessary to analyze previous historical patterns to identify exactly how intervention has promoted a change in ongoing trends.

Another criterium for defining a true carbon offset is that of additionality, which determines that offset projects should incur an incremental cost in comparison to straight forestry activities [Mendis and Gowen 1994]. If the incremental cost criteria is not adopted, investors would adopt for projects with the highest returns on investment, taking the least cost options first while leaving the higher cost options for the developing countries. Furthermore, these projects would not pass the "but for" test described above. One way to circumvent this distortion of the spirit of carbon offset is to only acknowledge projects in which the investing partner has no participation in the returns from the forest other than in terms of carbon quotas. This is the case of the projects established by the Face Foundation [Verweij 1994] and the New England Power Company [Marsh 1992].

FORESTRY OPTIONS FOR CARBON SEQUESTRATION

Carbon fixation through forestry is a function of the amount of biomass in a given area. Therefore, any activity or management practice that changes the amount of biomass in an area has an effect on its capacity to store or sequester carbon. Forest management practices can be used to reduce the accumulation of green house gases in the atmosphere through two different approaches. One is by actively increasing the amount or rate of accumulation of carbon in the area. The second is by preventing or reducing the rate of release of carbon already fixed.

Forestry approaches for promoting carbon accumulation

The most obvious approach to achieve the fixation of carbon is to plant trees. However, the effectiveness and feasibility of carbon sequestration through forestry varies widely depending on factors such as site, species and management practices.

Large expanses of under-utilised, degraded or deforested land with a low current value as carbon sinks which could be either afforested, reforested or rehabilitated are available throughout the world [Nilsson and Schopfhauser 1994]. The combination of climatic conditions favourable for tree growth, land availability and abundance of labour force favours the development of forestry schemes in tropical countries as opposed to temperate countries. Nabuurs and Mohren [1993] compared the rates of carbon sequestration of 16 forest types under different management practices and found that one of the most effective systems is the management of selectively logged rainforests. This is confirmed by Freedman *et al.* [1992], who estimated that an unrealistic amount of land was necessary to sequester a volume of carbon equivalent to the emissions of a single power plant through forestry in New Brunswick, Canada.

The choice of species has direct implications to its potential for carbon sequestration. Fast growing species accumulate higher amounts of biomass than slow growers during the same time period. However, their wood density tends to be lower, and therefore contains less carbon than slow growing hardwood trees (for wood density of dipterocarp timbers see Burgess 1966]. Due to this difference in growth rates, wood quality and growth requirements, different species require different management systems and have different end uses. These factors are directly linked to the rate of carbon accumulation of the forest. The growth cycle or length of the rotation defines for how long carbon will be stored in standing trees. Slow growing trees retain carbon for a long time during one growth cycle, while repeated cycles of fast growing trees are required to maintain levels of stored carbon for an equivalent length of time. For this reason, when planting fast growing trees, it is particularly important to consider the post-harvest management of the forest: whether to replant, manage it for natural regeneration, or to convert the forest land to other uses. The final use of the timber defines for how long carbon will remain stored in the form of wood products. Construction materials and furniture potentially retain carbon for a long period [Elliot 1985]; carbon in paper or fire-wood have the shortest post-harvest lives [Dewar 1990].

Different systems of tree planting offer different advantages and disadvantages. Fast growing species tend to be planted as mono-specific intensive plantations. Monocultures are a very efficient way of promoting biomass and carbon accumulation, and tend to be easier to manage than multi-species stands or natural forests [Evans 1992]. On the other hand they have several potential disadvantages such as reduction of biodiversity; higher susceptibility to fire, pests and diseases; high water usage, and increased erosion [Sawyer 1993]. Furthermore, because little is known about the growth requirements of fast growing trees indigenous to many tropical countries, plantations are frequently established using exotic species, with unknown consequences for the local fauna and flora [Sawyer 1993]. Conversely, most slow growing hardwood species tend to be planted in mixed stands. This is because most hardwoods are climax vegetation species and often require shading at the early stage of their growth cycle. Therefore, these species are better suited for enrichment planting [see chapter by Appanah and Weinland] or planting in the understorey of nurse trees of different species. This is the case for most climax tree species, including the dipterocarps [Appanah and Weinland 1993]. One advantage of enrichment planting is that it has a lower impact on the existing environment, since the changes to the structure and ecosystem of the original forest are only subtly changed [Lamprecht 1989]. However, the higher complexity of these systems makes it more difficult to manage, which has led to poorer success rates than have often been obtained in monoculture tree plantations [Tang and Chew 1980]. Since a considerable amount of carbon is already fixed in the secondary forests subjected to enrichment planting, the potential increase in the total carbon sink using this system is lower than that achieved through reforestation of bare land.

In areas where land use is primarily allocated to agriculture or grazing, the introduction of agroforestry practices could be a good way to promote carbon sequestration [Dixon *et al.* 1993b]. The introduction of trees in agricultural or pasture lands often has a series of beneficial effects such as crop diversification, risk reduction, better use of existing resources, erosion control, water catchment protection and fire-wood production [Lamprecht 1989].

There are already various projects and organizations using tree planting with the primary objective of carbon sequestration. One of the first initiatives on carbon sequestration through forestry was the CARE-Guatemala community-based agroforestry project partially funded by the Applied Energy Systems (AES), a US-based electrical power producer [Faeth *et al.* 1994]. Similarly, the Face Foundation of the Netherlands is conducting a series of forestry projects for carbon sequestration projects throughout the world. The projects funded by Face use different systems: enrichment planting of logged rainforests with the dipterocarp species in Malaysia [Moura-Costa 1993, Pinso and Moura-Costa 1993, Moura Costa *et al.* 1994a, b], the rehabilitation of degraded rainforests in Uganda [Okonya 1993], community-based reforestation of degraded pasture land with fast growing tree species in Ecuador, the restoration of forest degraded by acid-rain in a national park in the Czech Republic, and a series of small scale tree planting activities in the Netherlands [Face Foundation 1994, Verweij 1994]. Other examples of smaller carbon sequestration projects through forestry are given in Dixon *et al.* [1993a] and Faeth *et al.* [1994].

Although carbon sequestration is often discussed in the context of establishment of new forests, carbon fixation can also be achieved by improving the growth rates of existing forests. Depending on the condition of the forest, silvicultural treatments such as thinning, liberation treatments, weeding or fertilisation can greatly increase the growth rates of the forest stand [*e.g.* Korsgaard 1992, de Graaf 1986], improving their rate of carbon fixation. For estimates on the effects on carbon sequestration of a series of management practices and silvicultural treatments in temperate forests see the study by Hoen and Solberg [1994].

Forestry approaches for preventing or reducing release of carbon

The most obvious option for preventing the release of carbon fixed in vegetation is direct conservation of forests. A large proportion of land under forest cover is threatened with conversion into other forms of land use which have lower value as carbon sinks [Dixon *et al.* 1994b]. Some of the main pressures are conversion to agriculture and pasture, logging operations, and urbanization [World Resources Institute 1990]. Conservation of forests play a double role in relation to carbon sinks. Firstly, it prevents the emission of carbon which would be caused by decomposition of the forest biomass. It has been estimated that deforestation contributes to 30% of the current global CO_2 emissions [Houghton *et al.* 1992]. Secondly, conservation prevents the reduction in areas with potential for active carbon sequestration. There are many positive effects of using conservation as a means to preserve carbon pools, such as maintenance of unique ecosystems and wildlife, and protection of biodiversity. It also allows a further income from recreation and the ecotourism industry. It is estimated that conservation can promote a substantial increase in the global carbon pools [Brown *et al.* 1992]. An example in which conservation was used for carbon offset is the Oxfam/Coica project in the Amazon region, to offset the emissions of one power plant of the American utility company Applied Electric Systems. The approach of the project was to hire a group of lawyers to defend the land rights of indigenous populations against companies wishing to exploit their forest reserves for lumber, oil and mining [Faeth *et al.* 1994]. By protecting the forest, it was assumed that its value as a carbon sink was maintained.

Activities that reduce the rates of carbon emissions are also of great importance. These include reduction in rates of deforestation, introduction of techniques for controlled logging, and fire prevention. It is estimated that 15 million hectares of tropical forests are logged yearly throughout the world [Singh 1993], and the majority of logging operations in tropical countries are considered unsustainable and damaging [Poore 1989]. The implementation of techniques for reducing the impact of logging, thus avoiding unnecessary destruction of biomass and release of carbon, has great potential. This was the central idea behind the project initiated by the New England Power Company (USA), the environmental brokerage firm COPEC (Los Angeles, USA) and the forestry company Innoprise Corporation in Malaysia [Marsh 1992, 1993; Panayotou *et al.* 1994]. The objective of the project is to reduce by *ca.* 50 % the amount of damage to the residual stand through the adoption of strict guidelines for timber harvesting [Putz and Pinard 1993, Pinard 1994, see chapter by Marsh] adapted from the Queensland Selective Logging System [Crome *et al.* 1992]. The pilot phase of this project will finished in mid-1995, and preliminary estimates suggest that it is possible to prevent the release of *ca.* 35 t C ha^{-1} during the initial two years after logging using this approach [Putz and Pinard 1993, Pinard 1994]. In this project the hauling of felled trees was done by crawler tractors, and a certain amount of damage is inherent to this system. Further reductions in damage (and therefore C emissions) may be achieved if less destructive methods for timber hauling are adopted. The use of helicopters [Arentz 1992, Blakeney 1992], balloons [Dykstra 1994], or skyline systems [Bruijnzeel and Critchley 1994, Sarre 1992] have great potential for reduction of logging damage.

Fuel switching may also play an important role in reducing the release of GHG's to the atmosphere. Forests can be created with the sole objective of fire-wood production, reducing the use of fossil-fuels. Because fuel switching is a fully sustainable cyclic system, it is thought to be the most promising option for carbon sequestration in the long term [Grainger 1990]. This approach has received considerable interest in Thailand, where the FAO initiated a programme for research and development of combined energy systems based on forestry and hydro-electric power.

Another possibility to prevent unnecessary emissions is to promote fire control. In the last decade fire outbreaks destroyed millions of hectares of rainforests in Kalimantan and Sumatra, and it is expected that the incidence of forest fires will tend to increase in the next decade [ITTO 1994]. A combination of ground-based practices of fire prevention and control, and available remote sensing monitoring systems [Malingreau *et al.*

1989, DSE 1991] has great potential for reducing the frequency and extent of forest fires.

The approaches discussed above concentrate on the effect of management practices on vegetation only, and their consequences for carbon sinks. However, twice as much carbon is stored in soils as in vegetation [Dixon *et al.* 1994a]. According to the study of Nabuurs and Mohren [1993], tropical rainforests have up to 90 t C ha^{-1} (30 % of total carbon in this eco-system) and the humus-rich soils of boreal forests can have up to 150 t C ha^{-1} (60 % of total). The introduction of any technique that prevents or reduces soil loss has impacts on carbon sinks. This includes rationalization of use of heavy machinery, preferential use of selective felling as opposed to clear felling harvesting systems, the adoption of slope limits for plantations or logging operations, and the implementation of erosion-control techniques. Since most of the soil carbon is in the form of organic matter, management practices that promote an increase in soil organic matter can have a positive carbon sequestration effect [Dixon *et al.* 1994a, Johnson 1992, Lugo and Brown 1993]. A project has been proposed to preserve a whole watershed near the Panama Canal thus combining the benefits of managing both soil and vegetation for conservation of carbon pools [Faeth *et al.* 1994].

Different forest management practices sequester or prevent the release of different amounts of carbon from a given area, at different costs and different time frames (Table 1). It is important, therefore, that the choice of a method takes into consideration more than just the costs per unit carbon fixed. Each situation is different and the adoption of management practices or decisions on land use should take into account factors such as the impact on local populations, wildlife, biodiversity and local economy.

METHODS FOR QUANTIFICATION OF CARBON OFFSETS

As forestry-based carbon offset is becoming an activity of increasing importance, there is a need to define acceptable ways for quantification. This is particularly important for commercial transactions, such as the bi-national projects described in the previous sections. This section describes methods for quantification of carbon at a point in time as well as the potential carbon sequestration during a period of time. Two methods are described and compared.

Quantification of carbon stored in a site at a point in time

Determination of the amount of carbon stored in a site is done by quantifying the amount of biomass, necromass (*ie.* dead plant material) and soil organic matter and applying conversion factors [see Putz and Pinard 1993]. The first step for quantification is to measure the trees and calculate their biomass volume (for simplicity's sake, it is assumed that this site only has trees and no other vegetation). This is often done by taking dbh (diameter at breast height) measurements and using conversion formulas to estimate their biomass. The following formulas were defined for dipterocarps:

$1/H = 1/2D + 1/61$
where H is height in m, D is dbh in cm [Kira 1978];

$Ws = 0.313\ ((D^2H)^{0.9733})$
where Ws is stem biomass in kg [Kira 1978];

$Wb = 0.136\ (Ws^{1.07})$
where Wb is branch biomass in kg [Kira 1978];

Root biomass = 25 % of aboveground biomass [Chan 1982].

After quantification of the biomass stored in the tree stand, a conversion factor is applied to express it in terms of carbon. This conversion factor depends on the wood density of the species used. The conversion factor suggested for dipterocarps is:

$C = 0.5\ W$; where C is carbon and W is biomass [Chan 1982].

Quantification of soil carbon is done by determining the concentrations of soil organic matter through methods such as "loss on ignition" [Anderson and Ingram 1989].

This procedure produces a figure for carbon stored in a given area at a certain point in time. Repeated measurements are required in order to determine how the carbon pools change for time to calculate the sequestration potential of a particular forest type or management system.

Quantification of carbon sequestration during a period of time

Debate has arisen over how to quantify a carbon offset. Different methods have been proposed. The most common is based on the amount of carbon fixed in biomass at a certain point in time, usually the end of a rotation period. This will be called "carbon fixed" and it can be exemplified as the amount of carbon stored in planted trees at a certain time **t** after planting (Fig 1). On a yearly basis, the procedure for quantifying sequestration is to measure the trees every year, calculate their growth increment and calculate the amount of carbon fixed during that period (C1, C2 and C3, respectively; Fig. 2). Many estimates for carbon sequestration found in the existing scientific literature use this concept [*e.g.* Putz and Pinard 1993, Freedman *et al.* 1992, van Kooten *et al.* 1992].

One limitation of this approach is that it does not take into account the effect of time. Certain approaches should be rewarded for postponing the release of carbon stored in plant biomass to the atmosphere. In forestry terms that would mean the adoption of longer rotation periods, delaying the inevitable post-harvest decomposition of timber products. If only financial parameters are used, harvest would take place as soon as the point of maximum marginal return is achieved (approximately around $\mathbf{y_{mr}}$, Fig. 3) which often does not coincide with the point of maximum carbon "storage" capacity of the tree stand. Furthermore, determination of the amount **y** in Fig. 1 assumes a condition of stability, ie. that a given forest area will continue to store carbon at the maximum level in perpetuity. However, in most cases forests are kept for a finite period of time and it is necessary to look at what happens to it after this. In this situation, the slope of the post-harvest decomposition rate would determine the carbon sequestration efficiency of this approach, ie. low in the case of pulp and paper production (**p**, Fig.3) or high in the case of conversion to furniture (**f** in Fig.3). In the same way, if the trees are not harvested there must be a time-dimension for the remuneration of this foregone benefit (**nh** in Fig.3).

As decisions are often made within a defined time frame, the approach above is not ideal. An alternative approach for quantification is to use the concept of "carbon leasing". The quantification of carbon leased is slightly different, since the time factor is brought in, and the unit used should be t C ha^{-1} $year^{-1}$, rather than t C ha^{-1}. While for carbon fixed only the incremental carbon increase during a certain period of time can be claimed (**y** in Fig. 1), in the case of leasing, the cumulative amount of carbon sequestered is claimed at each period, as shown by the grey area in Figure 4. Therefore, the areas **CL1**, **CL2** and **CL3** can be claimed at times **t1**, **t2** and **t3** respectively (Fig. 4).

An advantage of the concept of carbon leasing is that it allows carbon sequestration to be treated as a service that can be stopped at any time, therefore requiring less long-term guarantees between the contracting parties. This is important since governments are often reluctant to adopt measures with perpetual consequences. An example would be to halt the logging of a given area for a certain period of time, "leasing" the forest in this area as a repository of carbon, without any assumption that this forest will not be logged after the period agreed. Another advantage is that this concept allows the comparison of forestry options with different time frames.

A comparison of the amounts of carbon fixed versus carbon leased for the same area would make it obvious that one unit of carbon leased should be worth much less than one unit of carbon fixed: one is a permanent asset while the other represents a service rate.

Applications to forestry and conservation practices

In this section we will discuss how the concepts described above apply to different forestry practices. The exact shape of the curves depend on technical parameters such as growth rates and biomass accumulation of a particular combination of site and species, and will not be discussed here.

The model of carbon sequestration for plantations and afforestation is given in Figure 5. Carbon fixed (**Cf**) until a given point in time (**t**) can be directly calculated by multiplying the biomass of planted trees by a conversion factor, which depends on the wood density of the species planted. The amount of carbon leased is illustrated by the shaded area $\mathbf{C_L}$. In the case of enrichment planting (Fig.6), the offset is the difference between the carbon accumulated in the planted forest ($\mathbf{C_{ep}}$) and the carbon in the untreated forest ($\mathbf{C_{uf}}$). A reduction in carbon is observed during site preparation, when planting lines are cleared of vegetation, but this would be compensated by the higher biomass increment of planted trees as compared to the untreated logged forest. Silvicultural treatments would have a similar trend of increasing biomass of a site compared to untreated.

Carbon offset by the use of reduced-impact logging (RIL) techniques (Fig.7), can be quantified as the difference between carbon stored in a forest logged conventionally and one logged according to RIL guidelines at some point in the post-logging (**t**). Immediately following logging no difference should exist between carbon stored in the two forests, if equivalent volumes of timber are removed from the two sites. However, more vegetation is damaged, and subsequently dies, in conventional logging. Therefore, as the logging debris decomposes, the carbon stored in a conventionally logged forest will decrease more quickly and to a lower level than will a forest logged with minimal damage to the residual stand. In addition, approximately 10 years following logging ($\mathbf{t_1}$), the logged forests should become sinks for carbon and the residual stand in a RIL forest will be healthier, consist of more higher density woods and will therefore sequester more carbon per ha than will a conventionally logged forest. These advantages are even greater in the case of less destructive hauling methods are used, such as helicopter[3] or skyline systems.

Carbon offset by conservation can be quantified as the potential reduction in carbon retained in a certain area caused by logging (Fig.8). In this case no net carbon sequestration occurs, and for this reason it is more adequate to use the concept of carbon leased ($\mathbf{C_L}$).

Although soil was not taken into account in these calculations, it is implicit that the use of good soil management techniques would improve the capacity of carbon sequestration of any forestry practice chosen.

Methods for comparing the carbon fixation effectiveness of different projects

The use of different methods of carbon quantification also creates difficulty for comparison between projects. Among the approaches suggested, the most simplistic is called *flow summation method* (Richards and Stokes 1994) and is based on the direct division of the total cost of the project by the amount of carbon fixed at a point in time. Its main weakness is that it does not takes into consideration time, both for quantification and for remuneration of carbon sequestration. Furthermore, it provides a "snap shot" of the carbon fixed at a certain point in time, and therefore the values derived from this method varies depending on the often arbitrary decision of when to quantify.

In order to reward projects that promote carbon fixation over a shorter period of time, Richards and Stokes (1994) suggested the *discounting method*. It consists of discounting the incremental carbon fixed in a yearly basis using a social discount rate (*ca.* 5 % per year). Then the present value of the project's costs is divided by the discounted carbon figure. This approach, however, tend to bias towards activities which prevent the release of carbon, such as conservation or reduced impact logging, instead of activities which actively remove carbon from the atmosphere in a lengthier way (*e.g.* forest establishment). This is because conservation activities internalise large amounts of carbon at the beginning of the project cycle, therefore suffering less from the effects of discounting. There remains the question of whether or not to use discounting techniques for environmental issues, as questioned by Price and Willis (1993).

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[3]. The question of how much fuel is consumed (and therefore carbon burnt) by helicopter logging is often asked. The amount of carbon released from fuel consumption during helicopter logging is *ca.* 500 kg C ha $^{-1}$, and the savings associated to this practice is up to *ca.* 150 t C ha^{-1} during the initial 10 years after logging.

An alternative non time-biased approach is the leasing concept. It consists of dividing the costs by the total amount of carbon leased during a project's life. Carbon lease can be calculated by using the integral of the of the carbon fixation curve for the project (for example, the shaded areas in Figures 4, 5, 6, 7 and 8). A similar approach called the *average storage method* was used by Dixon *et al.* (1991 1994b). It consists of dividing the project's costs by the sum of the total carbon sequestered in an area in a yearly basis, averaged over one full rotation.

Finite environmental services versus long term consequences

As mentioned before, forests only actively sequester CO_2 during the growing phase, after which carbon is stored in trees for as long as they are kept as living trees or as forest products (timber, paper, etc.). The decomposition of forest products eventually releases the carbon fixed in plant tissues back to the atmosphere. However, this may occur decades (or even centuries) after the forests were initially established. However limited, this period during which carbon is retained in plant biomass could play a very important role in reducing the overall concentration of GHG's in the atmosphere. For this reason, even though carbon offset through forestry does not provide a solution for eternity, it can be seen as an important interim environmental service of atmosphere cleansing while alternative sources of energy that do not entail CO_2 release are developed.

The following theoretical example illustrates this concept. Figure 5 shows the accumulation of carbon fixed by trees planted in an area which was initially bare. Assume that at the end of the growth cycle **t**, this forest was burned, immediately releasing the whole amount of carbon fixed in planted trees. Therefore the amount of carbon fixed at the end of this exercise is the same as the beginning, ie. zero. At first impression, one might assume that it was not worth planting trees at all. However, during the period of time **t** a total amount of carbon dioxide **C** was kept out of circulation, reducing the total concentration of GHG's in the atmosphere during that period and their deleterious environmental effects. An analogy would be the cooling effect that an air-conditioner has on its surrounding environment during the period that it is kept functioning.

A CASE STUDY

In this section, a case study of an ongoing carbon offset project is described, the INFAPRO (Innoprise-Face Foundation Rainforest Rehabilitation Project) in Sabah, Malaysia, which started in July 1992 (Pinso and Moura-Costa 1993).

Rationale for the project

The logging of dipterocarp forests accounts for a substantial proportion of the revenue of South East Asian countries. In order to maintain the economic returns derived from this sector, forest regeneration must be managed for sustainable yields. The high densities of natural stands in Sabah (Newbery *et al.* 1992) allow extraction rates of up to 120 m^3 ha^{-1} (Silam Forest Products, timber extraction figures). However, this results in substantial disturbance to the residual stand (Nussbaum *et al.* 1995; Appanah and Weinland 1990). In some areas the residual stocking and seedling bank of timber species is much reduced and artificial regeneration needs to be employed (Primack *et al.* 1987, Appanah and Weinland 1990). Enrichment planting is a technique for promoting artificial regeneration in which seedlings of preferred timber trees are planted in the under-storey of existing logged-over forests and then given preferential treatment to encourage their growth (Lamprecht 1986). However, the costs involved in artificial regeneration are often high and in some cases funds are not available from local sources.

Energy supply in the Netherlands is mainly provided by coal-fired power stations. The burning of coal produces emissions of CO_2 to the atmosphere, contributing to the greenhouse effect. In order to mitigate the emissions of electricity companies in the Netherlands, the Dutch Electricity Generating Board initiated a programme for planting forests through the Face (Forests Absorbing Carbon-dioxide Emissions) Foundation (Verweij 1994). However, it is not possible to find large enough areas in Europe to offset the amount of gases released to the atmosphere, since most of the land is already under agricultural or urban use.

The problems faced by Malaysia and the Netherlands were combined to generate practical solutions for both parties. In Malaysia, extensive areas are available for rehabilitation and/or planting of forests, whilst large industrial corporations in the Netherlands have the funds to invest in projects related to "environmental cleansing". In brief the idea is that Malaysia plants trees which absorb CO_2 emissions from the Netherlands (Marsh 1992).

Project description

The Innoprise-Face Foundation Rainforest Rehabilitation Project (INFAPRO) is a cooperative venture between Innoprise Corporation - a semi-government organization which has the largest forest concession in the state of Sabah, Malaysia, and the Face Foundation of the Netherlands. The objective of the project is to carry out rehabilitation of 25,000 ha of logged forests by enrichment planting and reclamation of degraded areas using indigenous tree species such as dipterocarps, fast growing pioneers and forest fruit trees, over a period of 25 years (Pinso and Moura-Costa 1993).

The main planting system consists of opening parallel lines (2 m width, 10 m apart) across logged forests and planting dipterocarp seedlings (every 3 m along the lines). Weeding is carried out every 3 months during the initial 3 years, after which time most of the planting seedlings have already attained a height greater than 3 m and are well established (Pinso and Moura-Costa 1993). Results achieved so far are very satisfactory, with initial survival rates around 87 % (Moura-Costa *et al.* 1994a, b) and growth rates of 1.2 cm dbh per year. Higher mortality rates are observed during the course of the first year (van Oorschot *et al.* 1994), and for this reason replanting is done at the end of the first three years. The long term nature of the project will enable the maintenance and silvicultural treatments required to sustain the growth rates achieved so far. It is expected that at the end of the 60-year growth cycle these forest will be exploited for timber, which belongs exclusively to Innoprise. However, timber harvesting will have to be done in a careful way, so that a healthy residual stand can again regenerate a well stocked forest in order to maintain a carbon pool for the Face Foundation, which has the exclusive rights to the carbon sequestered through the project.

Quantification of carbon sequestration

The amount of carbon sequestration expected from this project was estimated using figures from the literature and data from the project. The formulas used for calculation of biomass and carbon were those of Kira (1978) and Chan (1982). The following assumptions were used for the calculations in this paper:

- a pre-planting biomass of logged forest (5 years after logging) of 125 t ha^{-1} (based on Putz and Pinard 1993), growing at a rate of 1.0 t ha^{-1} $year^{-1}$ until planted trees reach 20 cm dbh. After that, it is assumed that the only increases in biomass in the site will be due to the growth of planted trees, while the biomass of the secondary forest matrix decreases at a rate of 1 % per year;
- an initial reduction in the site's biomass of 18 % as the result of the initial opening of lines, although trees with dbh larger than 10 cm and existing seedlings of commercial timber species and fruit trees were not removed during site preparation;
- after discounting unplantable points (ie. rivers, rocks, points already occupied by natural regeneration or trees) and the initial mortality (*ca.* 15% during first two months), an average of 280 seedlings establish per ha;
- dipterocarp trees grow at an initial rate of 1.6 cm dbh $year^{-1}$ during the initial 20 years; 1.2 cm $year^{-1}$ between year 20 and 40; and 0.8 cm $year^{-1}$ after 40 years (Vincent 1961 a, b; Tang and Chew 1980, Hassan *et al.* 1990, Moura-Costa *et al.* 1994 a, b). The initial rate of 1.6 cm $year^{-1}$ was chosen because this was the growth rate of the 50 fastest growing seedlings per ha (Moura-Costa *et al.* 1994a, b), which would be most likely the ones that survive until the end of the rotation;
- tree mortality of 2 % per year during the initial 30 years, and then 1.5 % per year (Hassan *et al.* 1990, Korsgaard 1992);
- a thinning operation is carried out 30 years after planting, removing 50 % of the existing trees;
- a recovery rate of 30 % of timber into wood products, which decompose at a rate of 7 % per year;
- a total of 80 t C ha^{-1} is stored in soil and necromass.

Figures for stand development and biomass production are given in Table 2. After approximately 10 years, planted trees will be large enough to compensate for the reductions in biomass assumed to result from site preparation. After 30 years, trees would have reached diameter *ca.* 42 cm, justifying a commercial thinning of 50 % of the stand. At this time, the total amount of carbon offset would have reached 170 t C ha^{-1} (before thinning). The remaining trees will be left to continue growing until the end of the 60-year rotation. The total amount of carbon offset stored in standing trees at the end of the rotation amounts to 183 t ha^{-1}, plus the carbon stored in the wood products harvested at year 30. The average yearly carbon offset will be 100 t C $ha^{-1}yr^{-1}$ during a 60-year rotation. Apart from the carbon benefits, a total of 346 m^3 of high quality timber will be produced during this time. These trees will eventually be harvested, but during the whole rotation the forest will be managed for promoting natural regeneration in order to maintain a healthy stand with a large carbon storage. Another factor to be considered is that the timber from enrichment planting could be classified as "sustainably produced" by wood certification schemes, possibly attaining higher market value (Prabhu 1994, Rowland 1994). Other benefits of enrichment planting include preservation of biodiversity, wildlife, and large areas of natural tropical forest, which otherwise would attain higher opportunity costs by conversion to plantations of fast growing trees or oil palm.

CONCLUSIONS

Carbon sequestration through forestry has the potential to play a significant role in ameliorating global environmental problems such as atmospheric accumulation of GHG's and climate change. Unlike other alternatives, forestry has social and economic side effects which are mostly benefic, ranging from maintenance of biodiversity and endangered habitats, to providing the home for forest communities.

The full development of this role of forestry is still dependent on international negotiations (Embree 1994). There is the concern that forestry-based carbon offsets could lead to a formula to sustain the economies of industrialised countries in detriment of the development of tropical countries (Mendis and Gowen 1994). A fair mechanism for joint implementation of projects, acceptable for both the industrialised and the developing countries, must be defined, creating a win situation for both parties. Agreement on the concept of joint implementation could promote an immense transfer of funds from the industrial to the forestry sectors never seen before. Such funds could well trigger a new "green revolution", initiating a new age for tropical forestry.

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Table 1: Estimated carbon sequestration with time-frame and costs for different forest activities in the tropics. Positive values reflect active carbon sequestration derived from a forestry option; negative values (between brackets) represent the potential emission of carbon which was prevented from the adoption of a forestry practice. The values shown do not necessarily come from the papers referred to, which were listed as suggestions for further reading.

Approach	Carbon sequestration or conservation[1] (t ha^{-1})	Time frame (years)	References
Plantations of fast growing species	100 - 200	10 - 20	Freedman et al. (1992) Dixon et al. (1991)
Enrichment planting with hardwoods	150 - 280	50 - 70	Moura-Costa et al. (1994a,b)
Agroforestry	90 - 150	20	Faeth et al. (1994)
Silvicultural treatments	90 - 150	30	Hoen and Solberg (1994)
Rainforest conservation	(300 - 400)	?	Faeth et al. (1994) IPCC (1992)
RIL[2] with tractors[3]	(35)/(80)	2/10	Putz and Pinard (1994)
RIL with helicopters[3]	(80)/(150)	2/10	-
Fuel switching (Fire-wood production)	(100 - 200)	10	IPCC (1992)
Fire protection	(250 - 350)	?	IPCC (1992)
Soil protection	(20 -30)	1	IPCC (1992) Faeth et al. (1994)
Soil improvement	1 - 2	1	Dixon et al. 1994a

1. Figures derived from straight summation of carbon flow (see Richards and Stokes 1994).
2. RIL = Reduced impact logging techniques.
3. First and second carbon figures refer to volumes estimated for 2 and 10 year time frames, respectively.

Table 2: Figures of growth, survival, biomass and carbon accumulation of enrichment planted and non-planted logged forests.

Year	B_{LF} (t/ha)	B_{ep} (t/ha)	N trees/ha	dbh (cm)	V_{trees} (m^3/ha)	B_{trees} (t/ha)	TC_{ep} (t/ha)	TC_{LF} (t/ha)	$C_{Wood\ products}$ (t/ha)	Cumulative C offset (t/ha)	Average C offset (t/ha/yr)
0	125	103	280	0	0	0	137	150	0	-13	0.00
5	130	107	253	8	5	9	145	153	0	-8	-13.87
10	135	111	229	16	29	51	170	156	0	15	-6.02
15	140	109	207	24	75	128	213	158	0	54	7.25
20	145	104	187	30	118	201	250	161	0	89	23.26
25	150	99	169	36	167	282	293	164	0	129	40.38
30	155	94	76	42	110	184	236	167	27	96	57.40
40	165	85	69	54	177	295	293	172	13	133	71.62
50	175	77	62	62	221	367	329	178	6	157	86.20
60	185	69	56	70	265	438	364	184	3	183	100.02

B_{LF} = Biomass of logged forest; B_{ep} = biomass of logged forest excluding enrichment planting; V_{trees} = volume of planted trees; B_{trees} = biomass of enrichment planted trees; TC_{ep} = total carbon in enrichment planted forest; TC_{LF} = total carbon in non planted logged forest; $C_{wood\ products}$ = carbon accumulated in wood products after harvesting at year 30; Cumulative C offset = $TC_{ep} - TC_{LF} + C_{wood\ products}$; Average C offset = Total cumulative carbon offset until a point in time averaged by the number of years.

Figure 1. Carbon stored (**y**) by planted trees at time **t** after planting.

Figure 2. Quantification of yearly amounts of carbon fixed (**C1**, **C2**, **C3**) by planted trees.

Figure 3. CO_2 offset by planted trees and post-harvest decomposition curves for pulp (**p**), furniture (**f**) or non-harvested options. $\mathbf{y_{mr}}$ = point of maximum marginal returns.

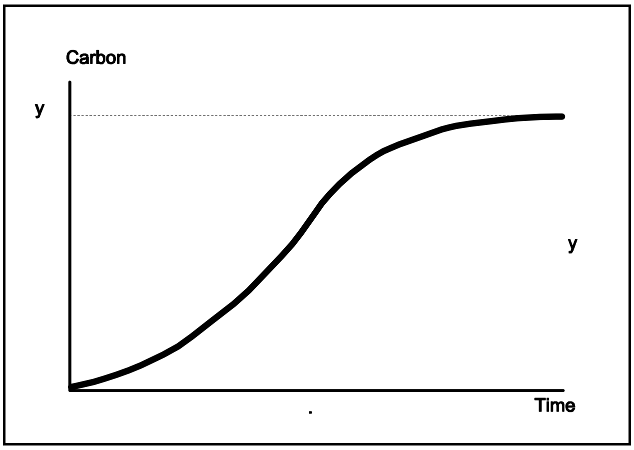
Figure 4. Quantification of carbon leased (**CL1**, **CL2**, **CL3**) at different points in time (**t1**, **t2**, **t3**).

Figure 5. Carbon offset by tree plantations. **Cf** = carbon fixed; $\mathbf{C_L}$ = carbon leased.

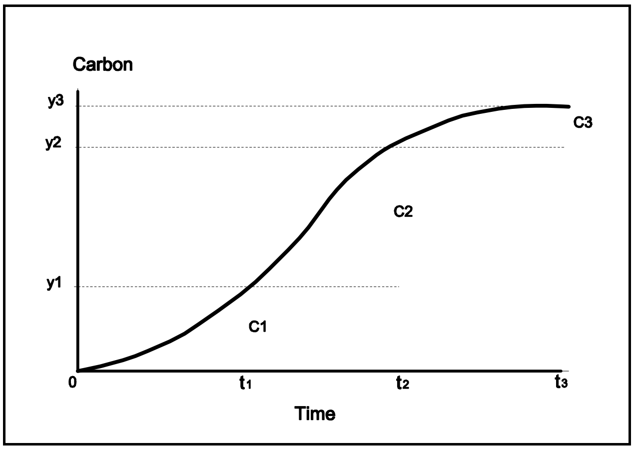
Figure 6. Carbon offset by enrichment planting. **Cuf** = carbon stored in an untreated forest;**Cep** = carbon stored in an enrichment planted forest.

Figure 7. Carbon offset by the use of reduced impact logging (RIL) techniques. **Cpf** = carbon stored in the primary forest.

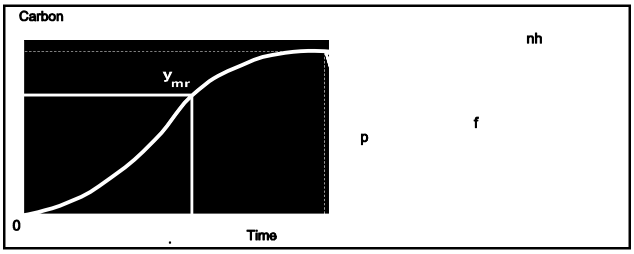
Figure 8. Carbon offset by conservation of an area originally designated to be logged. $\mathbf{C_L}$ **=** carbon leased.



1Figure 1: Carbon stored (**y**) by planted trees at time **t** after planting.



2Figure 2: Quantification of yearly amounts of carbon fixed (**C1**, **C2**, **C3**) by planted trees.



3**Figure 3:** CO_2 offset by planted trees and post-harvest decomposition curves for pulp (**p**), furniture (**f**), and non-harvest options (**nh**). $\mathbf{y}_{mr}$ = point of maximum marginal returns.

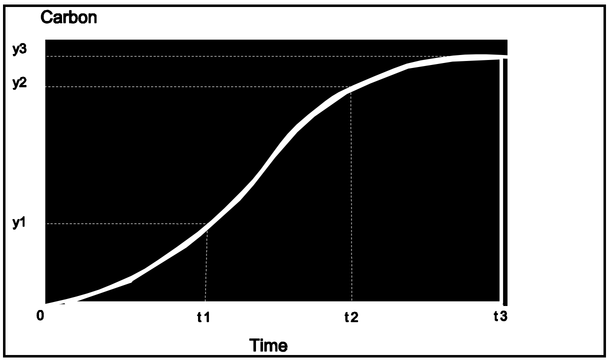


Figure 4: Quantification of carbon leased (**CL1, CL2, CL3**) at different points in time (**t1, t2, t3**).

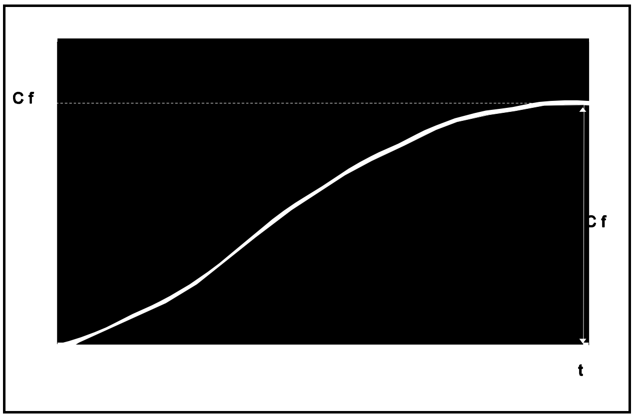
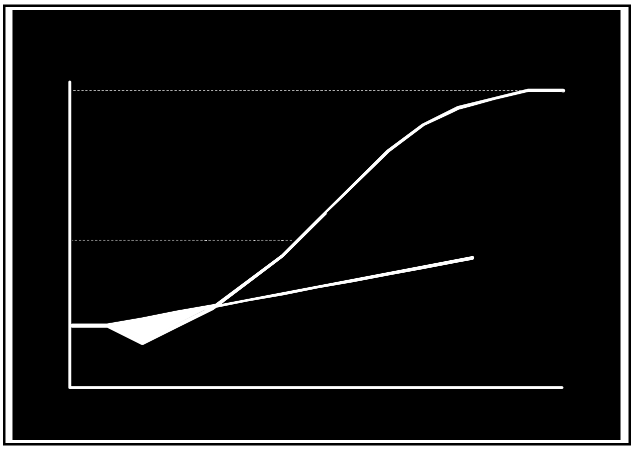


Figure 5: Carbon offset by tree plantations. **Cf** = carbon fixed; **C_L** = carbon leased.



6**Figure 6**: Carbon offset by enrichment planting. **C_{uf}**: **=** carbon stored in an untreated forest; **C_{ep}** = carbon stored in an enrichment planted forest at the end of the rotation.

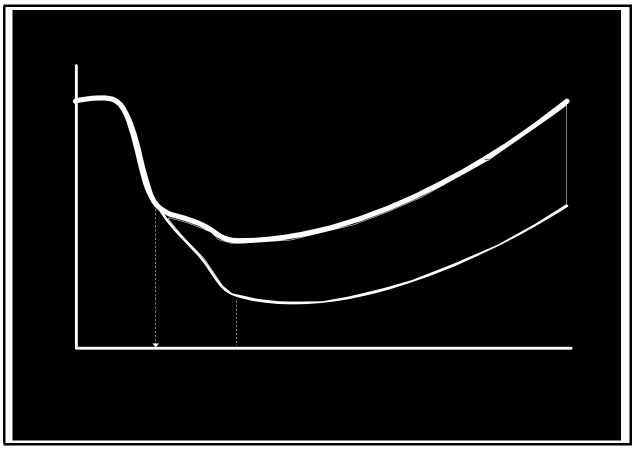


Figure 7: Carbon offset by the use of reduced impact logging (RIL) techniques. **Cpf** = carbon stored in primary forest.

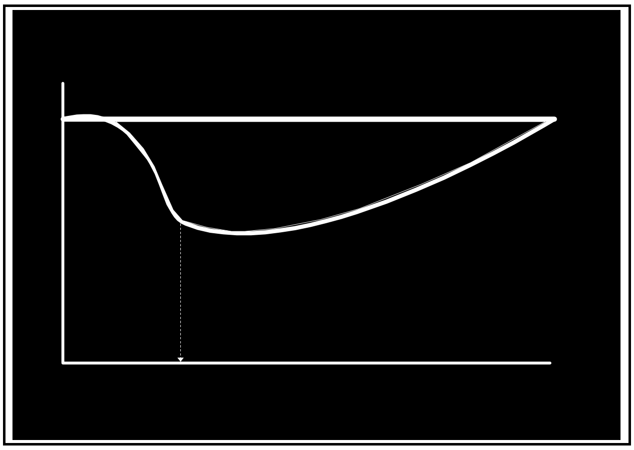


Figure 8: Carbon offset by protection of an area originally designated to be logged. **CL** = carbon leased.