PROCESSES AND LANDS FOR SEQUESTERING CARBON IN THE TROPICAL FOREST LANDSCAPE

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ABSTRACT. Balancing the C budget in the tropics has been hindered by the assumption that those forests not undergoing deforestation are in C steady state with respect to their C pools and thus with the atmosphere. The long history of human activity in tropical forests suggests otherwise. In this paper we discuss the forest compartments into which C can be stored, what the likely rates of storage are and for how long, and over which areas of the tropical landscape these processes occur. Results of our analysis suggest that tropical forests have the potential to sequester up to 2.5 Pg C yr^{-1} from the atmosphere if human pressure could be completely removed. Addition of agroecosystems and degraded lands could increase this estimate markedly.

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1. Introduction

The debate about the role of tropical forests as sources or sinks of atmospheric C is based mostly on different perceptions of how these forests function. What has hindered progress is the assumption that all tropical forest lands not undergoing active land-use change are mature or in C steady state with as much C being respired as is being fixed by photosynthesis, i.e., net ecosystem production is zero. What this assumption fails to account for is the long history of forest use by humans that has resulted in much of the tropical forest landscape being in less than a primary state. Biomass or C content of tropical forests has changed constantly over time as a result of past disturbances by people and natural catastrophes (Brown and Lugo, 1990a, 1992; Brown et al., 1991; 1992; Flint and Richards, 1991).

Before the wide-scale use of fossil fuels, and even today to a large extent, forest biomass has been used for a multitude of purposes including fuel and construction. When tropical countries relied solely on renewable resources (prior to the start of the industrial era), the net C flux from tropical forest lands could have already been in transient (i.e., not in steady state with respect to the atmosphere) because C in biomass per unit area could have been declining. Evidence suggests that this was the case and that the forests lands today contain less C per unit area than they could potentially store (Brown and Lugo, 1992; Iverson et al., 1992).

We suggest that essentially no forests are in C steady state, either with respect to all forest compartments or with the atmosphere, including secondary forests, logged forest, forest fallows, degraded forests (caused by biomass removal by illicit activities; Brown et al., 1991), naturally disturbed forests, and even mature forests (Lugo and Brown, 1986, 1992). We have argued that mature forests that are in C steady state with respect to all C pools in the forest cannot be in C steady state with the atmosphere (Lugo and Brown, 1986, 1992). All forests leach C into the soil profile and eventually rivers, therefore photosynthesis in the forest removes more C from the atmosphere than is returned. Therefore, if the C balance of tropical forests is not in steady state, how much C are they sequestering or can they potentially sequester if human pressure on them was reduced?

To address this question fully, we need to know in what ecosystem compartments C can be stored, what are the likely rates of storage and for how long, and over which areas of the landscape can these processes occur. This information has a practical value if serious consideration is going to be given to mitigating greenhouse gas emissions by sequestering C on the landscape. To meet this need, knowledge of the areas of land potentially and actually suitable for C sequestering is needed.

The objectives of this paper are to: (1) discuss the compartments and fluxes in tropical forest lands that lead to C sequestering, and their likely magnitude, (2) discuss briefly actual and potential forest land uses for sequestering carbon, and (3) present estimates of areas of land potentially suitable for C sequestering and the magnitude of the potential C sink for one tropical region.

2. Carbon Sequestering Processes in Tropical Forest Lands

The net balance of natural processes of the C cycle determine whether a tropical forest is a source or a sink of atmospheric C. Primary productivity fixes atmospheric C which then accumulates at various rates in above and below ground biomass, necromass (dead organic matter, excluding soil), and soil organic C. Fire and respiration pathways return C to the atmosphere. Depending upon the frequency of fires, C storage capacity can increase because of the production of charcoal which does not readily decompose. Carbon export (from soil and necromass) by leaching and the flow of goods (wood mostly) to the human economy transfer C to other systems where it can act as a sink.

Here we discuss the processes in tropical forest lands that have the potential to sequester C. We will focus on C accumulation in above ground biomass, necromass, and soil organic matter. Belowground processes have the potential to sequester C, but information needed for such an analysis is sorely lacking.

2.1. Accumulation in Above Ground Biomass

Observations of organic matter dynamics of long-term, small permanent tropical forest plots do not support the notion that they are in C steady state. Average net C accumulation in above ground biomass for 26 late secondary, slightly disturbed, or mature forest stands in Venezuela, grouped into five life zones, ranged between 1 to 2 Mg ha^{-1} yr^{-1} (Figure 1). The same is true of mature stands in Puerto Rico (Brown et al., 1983). In all cases, the balance (net wood

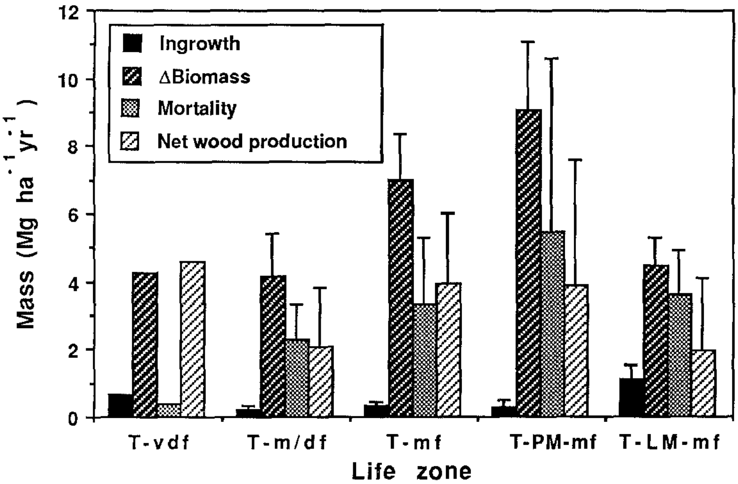

Figure 1. Organic matter budgets (values are means + 95% confidence interval) for 26 permanent plots in Venezuela, grouped into five life zones. T = tropical, vdf = very dry forest, m/df = moist transition to dry forest, mf = moist forest, Pm-mf = premontane moist forest, and LM-mf = lower montane moist forest.

production) between the sum of ingrowth (new trees entering the minimum diameter class of 10 cm) and biomass increment in live trees and the biomass lost by tree mortality was positive. Ingrowth into these stands tended not to be a significant C sink unless the stand was recovering from acute disturbance such as a hurricane.

Results of analysis of forest inventories done 10 yr apart in Peninsular Malaysia showed a similar trend (Brown et al., 1992). Carbon storage in vegetation of some inaccessible mature forests increased by 7 to 14%, while in recovering, previously logged forests, C storage increased by 7 to 152%. Accessibility to the forests explained the variation in the increases in C storage: forests with increased fragmentation (increase in the perimeter-to-area ratio and more accessible to humans) gained less C than forests with decreased fragmentation (less accessible to humans) in the 10 yr interval (Brown et al., 1992). Large increases in fragmentation led to biomass reductions and thus, potentially, to C sources to the atmosphere. In the case of the logged forests, a large proportion of the increased C storage was caused by ingrowth of the smaller trees (Brown et al., 1992).

Where is this C accumulating? We believe that a large fraction of the net C accumulation in above ground biomass occurs in the growth of older trees that get progressively larger with age. As a tree ages, its annual biomass increment continuously increases. Large trees (defined as those with a dbh > 70 cm and biomass of >5 Mg) generally occur at low densities in forests (less than 5 or so per ha), but they can account for more than 40% of the biomass of stands (Brown and Lugo, 1992; Brown et al., 1992). Such trees must be considered as long-term C sinks because they tend to survive for long periods. The presence and growth dynamics of large trees in forests may explain how C can continue to accumulate in forests for many decades or even centuries without any appearance of C excesses.

Change in species composition during forest succession is another way for biomass to continue to accumulate in a forest. Typically, mature forest species have higher density woods than early colonizing species (Smith, 1970; Whitmore and Silva, 1990). As a result, more C can be stored per unit wood volume produced. Weaver (1987) documented changes in the weighted density of montane forests in Puerto Rico from 0.61 Mg m^{-3} to 0.63 Mg m^{-3} or an increase of about 4% in mass per unit volume. Our biomass accumulation rates do not consider this process explicitly. These changes may be small per unit area of forest but can account for larger quantities when extrapolated over large forested landscapes.

The rate of above ground C accumulation in tropical forest lands ranges widely. Natural stands that are recovering from previous disturbances accumulate C in above ground biomass at the fastest rates in early stages (< 20 yr-old), i.e., up to 3.5 Mg $ha^{-1}yr^{-1}$ (Table 1). Older secondary forests accumulate biomass at rates of about half this amount (Brown and Lugo, 1990a). Fast growing plantations can accumulate C at rates as high as 15 Mg C $ha^{-1}yr^{-1}$ (Lugo et al., 1988).

2.2. Accumulation in Necromass

Most estimates of the quantity of organic matter in tropical forests have tended to ignore the amount of C in coarse woody debris (CWD) on the forest floor on the assumption that it is likely to be small relative to the C in biomass of live vegetation. Recent work

TABLE 1. Processes that create C sinks and their potential magnitude in the tropical forest landscape (from Lugo and Brown, 1992)

Process	Magnitude ($Mg\ C\ ha^{-1}yr^{-1}$)	Source
Biomass accumulation in forests >60-80 yr-old and logged forests	1-2	Brown and Lugo, unpublished data
Biomass accumulation in secondary forest fallows, 0-20 yr-old	2-3.5	Brown and Lugo, 1990a
Biomass accumulation in plantations[a]	1.4-4.8	Brown et al., 1986
Accumulation of coarse woody debris in:		
forests >60-80 yr-old	0.2-0.4	Brown and Lugo, unpublished data
forests 0-20 yr-old	0.2-0.3[b]	Brown and Lugo, 1990a
Accumulation of SOC:		
background rates	0.02-0.03	Schlesinger, 1990
forest succession	0.5-2.0	Brown and Lugo, 1990b
plantations <40 yr-old	0.5-2.0[c]	
conversion of cultivation to pasture/grassland	0.3-0.42	Lugo et al., 1986

[a] Weighted average rates across all species and age classes.

[b] Two studies given in Brown and Lugo (1990a) report an average amount of coarse woody debris at age about 20 yr of 8.5% of the aboveground biomass; we assumed this percent of the biomass accumulation rate goes into coarse woody debris during the 20 yr period.

[c] Assumed rates of SOC accumulation similar to secondary forests.

suggests otherwise. The few data available for late secondary and mature tropical forests suggest that the standing stock of CWD may be about 10 to 40% of the above ground biomass (Greenland and Kowal, 1960; Saldarriaga et al., 1986; Uhl et al., 1988; Uhl and Kauffman, 1990). Further, annual rates of production of CWD can range from 0.2 to 4 Mg C ha^{-1} yr^{-1} (unpublished data of authors, see also Figure 1 for mean rates). This large pool, high rate of production, and its slow decomposition rate makes this compartment another potential long-term sink of C (Table 1). We have found that wood decomposition can be slower than the growth of new wood in a disturbed stand (unpublished data of authors). Thus, by retaining CWD *in situ*, a stand gains additional C (as above ground necromass) that can last for a little as 30 yr to as long as 200 yr depending upon the mix of, and the decomposition rates of, the wood.

2.3. Accumulation as Soil Organic Carbon

Soil organic C (SOC) is a long-term storage compartment for atmospheric C and may take on the order of millenia to reach steady state levels (Jenny, 1980). Schlesinger (1990) recently confirmed this trend when he showed that soils can continue to accumulate SOC over thousands of years (we define this continued accumulation as the background rate, Table 1).

There are large losses of SOC associated with permanent agriculture (Detwiler, 1986) but not with short-term use by shifting agriculture (Ewel et al., 1981; Ramakrishnan and Toky, 1981)). Soils recover their SOC following abandonment of agriculture to forest succession, with the rate depending upon life zone (Figure 2a, Table 1). Forests in moist or wet life zones recover SOC faster than in dry life zones, but all appear to reach levels of SOC approaching those of nearby forests in about the same length of time (about 50 yr).

Conversion of forests to pastures often results in no loss or gains in SOC compared to nearby, native forests (Figure 2b). Furthermore, resampling of cultivated sites that had been converted to pastures showed increases in SOC over several decades (Table 1). In other words, soils under pasture can be C sinks, regaining some of the C that was released during clearing. High rates of root production by grasses may explain why pastures accumulate SOC (Cerri et al., 1991).

Soil organic matter will recover under forest plantations at rates similar to or faster than secondary forests (Figure 2c). Differences in rates of SOC accumulation are caused by differences in species and environmental factors (Lugo et al., 1990). Some species produce more litter and roots than others, thus producing more organic inputs which eventually influences SOC. Clearly, this species effect must be considered in plans for enhancing C sequestering.

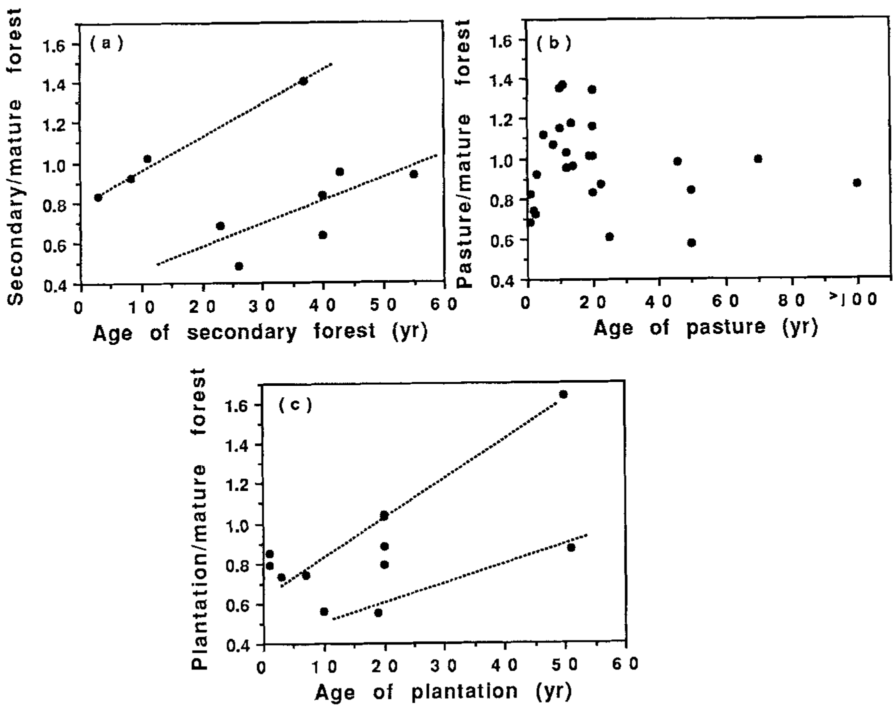

Figure 2. The ratio of soil organic C in (a) secondary forests, (b) pastures, and (c) plantations to paired mature forests versus age. Lines in (a) and (c) are drawn in by hand to illustrate range of likely rates of soil C sequestering. Data are from Lugo and Brown (unpublished paper).

3. Forest Land Uses for Sequestering Carbon

Land-use change in the tropics can be brought about by human and natural events. These changes in forest land use are complex, with forests undergoing degradation, logging, and conversion to shifting cultivation/forest fallow, permanent agriculture, and urban lands, as well as the converse.

In addition to outright forest clearing, large areas of tropical forests experience some measure of human degradation that affects their biomass and forest composition (Brown et al., 1991, 1992; Flint and Richards, 1991; Brown and Lugo, 1992; Iverson et al., 1992). The intensity of this biomass degradation varies from the removal of one or two valuable large trees per hectare, often illicitly, to clearing of small areas (Brown et al., 1991).

All these land-use changes (discussed in detail by Lugo and Brown, 1992) have numerous implications for the C cycle because each land use has a particular potential and actual C density and functions at a particular speed of C accumulation and export. During the time interval between events that reduce the biomass of a stand, C accumulates at various rates by regrowth, retention of necromass or wood products, and/or increased SOC. All these processes must be considered when doing a complete accounting of C fluxes in the tropical landscape.

Because forest lands undergo reductions in their C pools when they are converted to other uses, they have the potential to regain this C if human pressure is removed or reduced. Logged forests are a clear example; most logging operations extract a few trees per hectare of a given diameter and then the forest is allowed to recover for many decades before it is logged again.

Clearly lands used for food production have little chance of being abandoned (except for those lands under shifting cultivation). However, alternative soil organic matter management or conversion to agroforestry systems, permanent tree crop plantations (rubber, oil palm, cacao, etc.) or pastures could improve the sequestering capabilities of these lands as well as make them more sustainable. These possibilities and their effect on C sequestering will not be discussed here. Instead we will concentrate on present forest lands (mature, logged, and plantations) because they have the potential to sequester significant amounts of C to help balance the net flux of C to the atmosphere from tropical deforestation (Lugo and Brown, 1992).

4. Estimating Lands Potentially Suitable for Carbon Sequestering: South/Southeast Asia as a Case Study

Here we will discuss preliminary results of current research designed to identify forest lands in continental South/Southeast Asia suitable for C sequestering. As important as the results being presented here is the methodology that we have developed, which we believe is the approach needed to better estimate C sequestering on the landscape. Land areas alone are not enough, as we have shown, because C sequestering rates are dependent on environmental factors, as are the potential steady state C pools.

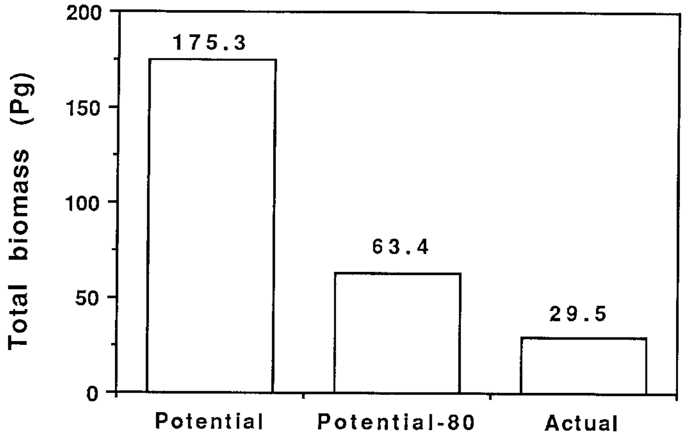

Figure 3. Estimates of potential forest biomass, and potential and actual forest biomass as of about 1980 for continental South/Southeast Asia (from Iverson et al., 1992).

The amount of C that can ultimately be sequestered in forest vegetation (potential C pool) on the landscape is related to the amount of biomass that the biophysical factors of climate, soils, topography, and elevation can support. Using geographic information systems technology (GIS) and digital maps of these biophysical factors, estimates of the potential above ground biomass (or C pool), in digital map form, have been made for South/Southeast Asia (Iverson et al., 1992). This digital map was then overlain with a forest map as of about 1980 to produce a potential forest biomass map for this time period (potential biomass-80; Iverson et al., 1992). The final step was to then add the influence of humans that cause biomass reductions through many types of activities, discussed above, to produce a digital map of actual forest biomass. This biomass reduction was done by taking into consideration human population densities, presence/absence of shifting cultivators, historical accounts of the area, forest inventories, and the advice of experts on the region (Iverson et al., 1992).

This approach resulted in three maps of forest biomass and three estimates of the total biomass for these three conditions (Figure 3). The overall decrease in above ground biomass caused by the long history of human impacts on the forest lands of continental South/Southeast Asia was 83%. The first decrease, between the potential biomass and potential biomass-80 (64%

reduction), represents the cumulative effect of deforestation only in the region. The further decrease of an additional 53% represents the impact of biomass degradation on present forest lands, including planned logging operations.

Iverson et al's. (1992) analysis considered C in above ground biomass only. We have added estimates for C in below ground biomass and coarse woody debris to complete the picture (Table 2). Clearly, achieving the potential C is unrealistic because humans cannot be removed from the landscape completely. However, achievement of the potential C pool in forest lands as of about 1980 is more realistic (although the forest areas in this region have declined by at least another 9% during the last decade [Food and Agriculture Organization, 1991]), particularly if economically sustainable practices were implemented on all agricultural lands. Thus the potential amount of C that can be sequestered in forest vegetation in the region is 28 Pg (Table 2). Accumulation of organic C in any degraded soils of the forest lands is not included here which could increase the potential amount.

Although we refer to the amount of C that can be sequestered as "potential", some of this is actually being sequestered by those processes described in Table 1 in previously logged forests, inaccessible forests, or forests now under protection as described above for Peninsular Malaysia, for example. At present we have not separated these forests from other forest lands still undergoing degradation, thus we refer to the whole amount as potential.

Knowing the total amount of C that potentially can be sequestered in continental South/Southeast Asia is only part of the issue; annual rates and over what time interval are also important. The range in magnitude of C sequestering rates in forests is very much a function of climate or life zone, thus the need to add this level of detail to the analysis.

In the absence of a reliable digital life zone map, we reclassified an ecofloristic zone (EFZ) map produced by the Food and Agriculture Organization (1989). This map distinguished 36 zones based on climate (rainfall and its regime, length of the dry season, temperature, and relative humidity), physiography, and edaphic factors (Food and Agriculture Organization, 1989). We reclassified these 36 zones for continental South/Southeast Asia into six that approximated a simple life zone classification (based on the groupings given in Brown and Lugo, 1982) (Figure 4).

TABLE 2. Potential and actual C pools in forest vegetation of continental South/Southeast Asia and potential magnitude of C sequestering

	Pg C			
	Aboveground vegetation[a]	Below-ground[b]	Coarse woody debris[c]	Total
Potential (without humans)	88	18	26	132
Potential as of 1980	32	6.3	9.5	48
Actual as of 1980	15	3.0	2.2	20
Potential amount of C sequestering[d]	17	3.3	7.3	28
Potential rate of C sequestering[e]	**---0.25 Pg yr^{-1}---**			

[a] From Figure 3, and using 1 Pg of biomass = 0.5 Pg C

[b] Assumed belowground mass = 20% of aboveground (Brown and Lugo, 1982)

[c] Assumed coarse woody debris was 30% of potential aboveground biomass (mature forests) and 15% of actual biomass (disturbed forests) (see text).

[d] Estimated by difference between potential as of 1980 and actual C pool as of 1980

[e] Estimated as follows: first, the distribution of forest areas, based on their ranking to sequester C by ecofloristic zone (EFZ, Figure 5) was used to estimate a weighted rank for each EFZ. Then the rates in Table 1 were applied differentially, based on their C sequestering rank and EFZ, to the areas of each EFZ shown in Figure 4.

Clearly, the lowland seasonal forest zone dominates the region (53% of the total area), due in the most part to the common occurrence of this zone in India, by far the largest country in the region. This large area of the lowland seasonal zone will dominate the rates of C sequestering. The lowland moist zone, the one likely to have the highest C sequestering rates, occupies about 25% of the region.

The next important issue is how much of the potential C sequestering (Table 2) occurs in which EFZ? To address this question, we subtracted the actual forest biomass map from the

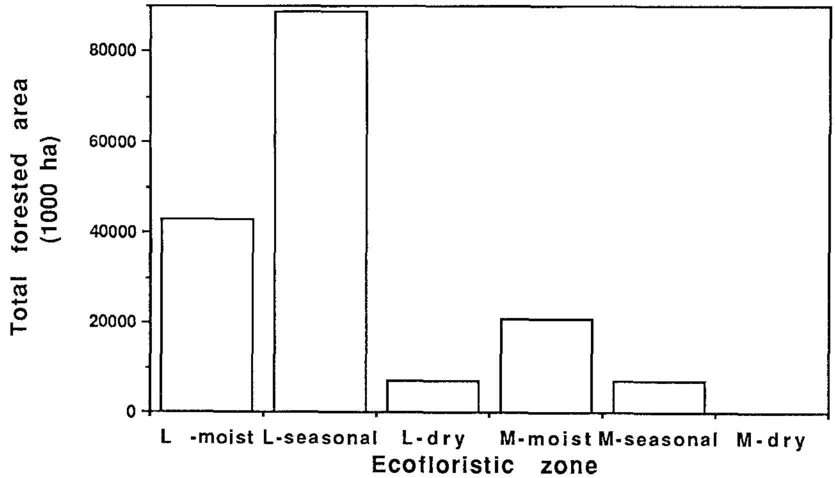

Figure 4. Areas of forest in continental South/Southeast Asia, as of about 1980, grouped into six ecofloristic zones (reclassified ecofloristic zone map produced by the Food and Agriculture Organization, 1989). L= lowland zones and M= montane zones.

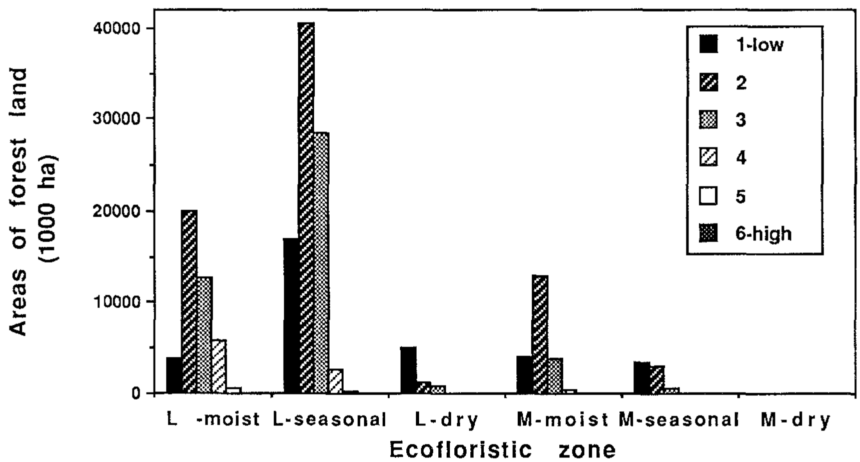

Figure 5. Areas of forest in South/Southeast Asia, as of about 1980, ranked according to their ability to sequester new C in vegetation, and grouped into six ecofloristic zones (see legend to Figure 4 for source of ecofloristic zones and key to symbols).

potential biomass-80 map and, using GIS techniques, overlaid this with the reclassified EFZ map. This resulted in the distribution of areas, classed by their ability to sequester C from low to high, by EFZ shown in Figure 5. Very little forested area has the ability to sequester high amounts of C; most of the total area can sequester low amounts (rank of 1 to 2).

Using the information in Figure 5 and in Table 2, the annual rate of potential C sequestering in forests of the region was estimated to be 0.25 Pg yr^{-1}, which could occur for more than 100 yr (annual rate divided into the total amount given in Table 2). This seems a small amount compared to the present emissions of C from fossil fuels (about 6.0 Pg yr^{-1}). However, the forest area in the region is only about 10% of the total tropical forest area. If rates similar to these were assumed to occur over the whole tropics, then the total could be 2.5 Pg yr^{-1}, or a little under half that produced from fossil fuel. And, as C sequestering in agroecosystems and degraded lands is not included, the total amount could be even more significant. An analysis by Lugo and Brown (1992), without the geographical component, produced an estimated C sink of 1.5 to 3.2 Pg yr^{-1} for all tropical forest lands.

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