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CARBON EMISSIONS AND SEQUESTRATION IN FORESTS: CASE STUDIES FROM SEVEN DEVELOPING COUNTRIES

VOLUME 1: SUMMARY

Willy Makundi, Jayant Sathaye, and Omar Masera Cerutti

Series Editors: Willy Makundi and Jayant Sathaye

August 1992

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Climate Change Division
Environmental Protection Agency
Washington, DC, USA

Energy and Environment Division
Lawrence Berkeley Laboratory
Berkeley, CA, USA

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Willy Makundi, Jayant Sathaye, and Omar Masera Cerutti

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PREFACE

In January 1990, scientists and policymakers from around the world convened for a meeting of the Intergovernmental Panel on Climate Change (IPCC) in São Paulo, Brazil, to continue the ongoing discussions on emissions of greenhouse gases and global climate change. As part of the effort to further understand the sources of carbon dioxide (CO_2) and other major greenhouse gases, LBL and the University of Sao Paulo, with support from the U.S. Environmental Protection Agency, organized a workshop on tropical forestry and global climate change which was attended by the IPCC conference participants. Discussions at the workshop led to the establishment of the Tropical Forestry and Global Climate Change Research Network (F-7). The countries taking part in the F-7 Network -- Brazil, China, India, Indonesia, Malaysia, Mexico, Nigeria and Thailand -- possess among the largest tracts of the Earth's tropical forests and together experience the bulk of tropical deforestation.

The following research objectives were identified as the F-7 Network's priorities:

1. To improve and expand the body of knowledge about the extent of tropical deforestation through the use of available tools, including remote-sensing imagery, detailed biomass measurements and existing models.

2. To explore the dynamics of forest land use within the context of individual country's social and economic structures.

3. To identify alternative response options aimed at stemming deforestation and promoting sustainable land-use practices while maintaining each country's economic well-being. Meeting this objective includes carrying out an assessment of the economic costs of implementing various mitigative policies.

One of the strategies of this project was to rely on the work of indigenous researchers and institutions from each of the participating countries. This approach allowed for the integration of more precise, on-site information, some of which had not been previously published, into the more general and universally available base of knowledge. The Lawrence Berkeley Laboratory (LBL), which employed a similar approach to carry out a study on carbon emissions from energy use in developing countries (LDCs) (see Sathaye and Ketoff 1991), coordinated the work of the researchers and provided scientific and institutional support for the F-7 participants. The U.S. Environmental Protection Agency (EPA) financed the F-7 research.

This paper summarizes the findings of seven country studies from the F-7 Network.[1] The information contained in this report represents the results of the first phase of the F-7 project, which had the explicit aim of providing quantitative data on forestry-related carbon emissions in the F-7 countries. The individual country papers on this topic are being published

[1] The results of the Nigeria study are still under preparation and thus are not included in this summary. A separate case study of Nigeria will be published along with individual papers for all the other participating countries.

separately. The next stage of the process will involve an assessment of response options in the forestry sector and the economics of undertaking these measures. The following scientists and institutions participated in the research:

Country	Expert	Institution
Brazil	Philip Fearnside	Departmento de Ecologia Instituto Nacional de Pesquisas de Amazonia Manaus-Amazonia
China	Xu Deying	Research Institute of Forestry Chinese Academy of Forestry Beijing
India	N.H. Ravindranath B.S. Somashekhar Madhav Gadgil	Centre for Ecological Sciences Indian Institute of Science Bangalore
Indonesia	Edy Brotoisworo	Institute of Ecology Padjadjaran University Bandung
Malaysia	Roslan Ismail Ismariah Ahmad Faizah Fakhruddin	Forest Research Institute Kepong Kuala Lumpur
Mexico	Rodolfo Dirzo Minjarez Omar Masera Cerutti María de Jesús Ordóñez	Centro de Ecología Universidad Nacional Autonoma de México Mexico City
Thailand	Somthawin Patanavanich Ladawan Atipanumpai	Thailand Development Research Institute Faculty of Forestry, Kasetsart University Bangkok
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The opinions expressed in this work are those of the authors and do not necessarily reflect those of the affiliated institutions or of the respective governments.

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ABSTRACT

Forests are a major source of carbon dioxide emissions in developing countries, in most cases far exceeding the emissions from the energy sector. To date, however, efforts at quantifying forestry emissions have produced a wide range of results. In order to assist policymakers in developing measures to reduce emissions' levels and to increase carbon sequestration, the Tropical Forest Research Network (F-7) has undertaken this effort to improve the precision of emissions estimates and to identify possible response options in the forestry sector. This paper summarizes the results of one component of this work. The Tropical Forest Research Network (F-7) was established in 1990 as part of the Intergovernmental Panel on Climate Change's (IPCC) activities in examining growing emissions of greenhouse gases and their potential impact on the global climate. Unlike past methods, this study relied on a network of participants from developing countries to prepare estimates of carbon emissions. The participating countries -- Brazil, China, India, Indonesia, Malaysia, Mexico and Thailand -- currently represent an estimated two-thirds of the annual deforestation of closed moist forests. This study gives an estimate of 837 million tonnes of carbon emissions from deforestation and logging in the F-7 countries in 1990. A proportional projection of these estimates to the tropical biome shows that the total carbon emissions are between 1.1 and 1.7 billion tonnes of carbon, with a working average of 1.4 billion tonnes per year. While most previous studies have overlooked the importance of carbon sequestration resulting from forest growth and afforestation activities, this study estimates short- and long-term uptake. The uptake from growing stock for the F-7 countries was estimated at 374 million tonnes of carbon in 1990, while the committed sequestration from base year activities was estimated at 367 million tonnes of carbon. This work also provides estimates of emissions and uptake from China, which past studies rarely have included. This summary will be followed by individual reports by each of the participating countries, which will include detailed evaluations of possible response options. Estimates for Nigeria are also under preparation.

1. INTRODUCTION

Recent research has provided scientists and policymakers with a far better understanding of the critical influence of emissions of greenhouse gases (GHGs) on the global climate. A number of studies indicate that rising atmospheric concentrations of carbon dioxide (CO_2), chlorofluorocarbons, methane, nitrogen oxides and tropospheric ozone can lead to increases in global temperatures and other environmental changes (IPCC 1990, IPCC 1992, OTA 1991, etc.). Current levels of atmospheric carbon dioxide exceed pre-industrial levels by 26 percent (Keeling *et al.* 1989a,b). At the present rate of growth, emissions of GHGs could lead to a 1.3° to 2.5° C rise in mean global temperatures by the year 2020 -- an increase which would surpass the cumulative change in global temperature over the past 10,000 years (IPCC 1990, Houghton *et al.* 1990).

In industrialized countries the combustion of fossil fuels accounts for the vast majority of all anthropogenic emissions of CO_2. Various studies have quantified these emissions, placing them in a reasonably narrow range (e.g., IPCC 1992 estimates that global emissions from fossil fuel use totaled 6.0 ± 0.5 gigatonnes of carbon in 1989). In developing countries (LDCs), where fossil fuel use per capita is far lower, the clearing and conversion of forests often account for a major portion of all CO_2 emissions. Despite widespread recognition of the substantial contribution forests make to global emissions of carbon dioxide, great uncertainty exists about the quantity of CO_2 emitted from forest-related activities.

The variation in the available global estimates, presented in Table 1, reflects this uncertainty. Estimates of worldwide carbon emissions from forest clearing for the late 1980s range from 0.6 to 2.8 gigatonnes of carbon (GtC)/year (Table 1). There also has been a lack of consensus on estimates of emissions from forest clearing at the national scale. Calculations of CO_2 emissions from forestry in the F-7 countries (i.e., Brazil, China, India, Indonesia, Malaysia, Mexico and Thailand) by Myers (1989), WRI (1990) and the United Nations Food and Agricultural Organization (FAO 1988) differ dramatically (Table 2).

A key problem stems from an incomplete knowledge about the many factors that affect emission levels. A precise measurement of forestry emissions requires detailed data on the extent of forested areas, on rates of deforestation and vegetation regrowth, as well as on physiological parameters, including the stock of biomass, the carbon content of wood and soil, rates of decomposition and oxidation and the ecosystem's capacity to accumulate carbon. In the past, many studies have relied on aggregate parameters and generalizations that do not take into account the wide variations found among different forest types, regions and countries. In addition, the use of inconsistent, and often unstated, definitions of deforestation and emissions and varying base years has led to some confusion and has made cross-study comparisons difficult.

Table 1. Estimates of Carbon Emissions from Deforestation in Tropical Countries, 1980 and 1989[a,b]

Source		Carbon Emissions (GtC/year)
1980	Seiler *et al.* (1980)	0.4 - 1.2
	Molofsky *et al.* (1984)	0.6 - 1.1
	Houghton *et al.* (1987)	0.9 - 2.5
	Detwiler & Hall (1988)	0.4 - 1.6
	Hao *et al.* (1990)	0.9 - 2.5
	Myers (1989)	0.4 - 1.4
1989	Myers (1989)	2.0 - 2.8
	Houghton (1991b)	1.1 - 3.6
	IPCC (1990)	0.6 - 2.6

Notes:

a. Most of these estimates include open and closed forests, with the exception of Molofsky and Myers's estimates for 1980, which only include closed forests.

b. In past studies, definitions of "open" and "closed" forests have varied. The FAO defines closed forests as areas with a high proportion of tree cover and no continuous grass layer. The FAO defines open forests as areas characterized by a combination of forests and grasslands with tree cover ≥ 10 percent and a continuous layer of grass across the forest floor. (FAO 1988 cited in WRI 1990). In contrast, the United Nations Economic Commissions for Europe (ECE) defines closed forests as areas with >20 percent crown cover that are used primarily for forestry. Open forests, according to the ECE definition, are areas not devoted to agriculture, with 5-20 percent crown cover, with an area no greater than 1/2 hectare covered with groups of trees, or have at least one-fifth of their area covered by stunted trees or shrubs (ECE 1985 cited in WRI 1990).

Table 2. Estimates of Committed Carbon Emissions from Forest Conversion Activities and Deforested Area

Country	Deforestation (10^6 ha)			Committed Emissions (MtC)		
	Myers 1989[a]	WRI 1980s	FAO early-to-mid-1980s	Myers 1989[a]	WRI 1987[b]	FAO early-to-mid-1980s[c]
Closed Forests						
Brazil	5.0	8.0	1.5	454	1200	163
China	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
India	0.4	1.5	n.a.	41	140	n.a.
Indonesia	1.2	0.9	0.6	124	220	58
Malaysia	0.5	0.3	0.1	50	38	9
Mexico	0.7	0.6	0.6	64	32	64
Thailand	0.6	0.4	0.4	62	94	26
Subtotal for F-7 Countries	8.4	11.7	---	795	1,724	---
Closed Forest Total	13.9	16.2	---	1400	---	---
Open Forest Total	---	4.5	---	1000	---	---
Global Total	---	20.7	---	2400	2800	---

Notes:
a. Only includes tropical forests.
b. National emissions figures are for all land-use changes, primarily deforestation of closed forests.
c. These emissions calculations were derived from estimates of deforested area by FAO (1988) and estimates of carbon density by Houghton (in Myers 1989).
d. The Malaysia figure is included in the global total.

Sources: Myers 1989; WRI 1990; FAO 1988.

This work uses case studies to address the need for more accurate, detailed data and a consistent framework in the analysis of carbon emissions from changes in forest cover in developing countries. The seven developing countries represented in this work together account for almost two-thirds of worldwide deforestation[2] and for more than half of global carbon emissions from the clearing of closed tropical forests according to two recent studies (calculated from Myers 1989 and WRI 1990; see Table 2). In-depth studies at the country-level represent a major step towards creating a more accurate picture of CO_2 emissions worldwide. Simultaneously, the country-level approach allows for a careful analysis of the specific factors spurring deforestation at the national scale and thereby provides a better understanding of the types of national policies necessary for reversing current trends. This paper presents a summary of the results of the country-level reports (each of which will be published separately at a later date). Follow up studies carried out by each of the participating experts will use the information provided here to address policy measures for reducing forestry emissions and analyze the economic costs of implementing alternative response options.

2. METHODOLOGY

2.1 Approach

In order to achieve its objectives, this study relied on the contributions of institutions and scientists from each of the participating countries. The work of these researchers was coordinated at a central location, the Lawrence Berkeley Laboratory, which also offered scientific and institutional support and carried out the final aggregation of the estimates. The information culled from each of the on-site studies was supplemented by data from the international literature. In cases where neither published nor unpublished information was available, the researchers used local expertise to derive reasonable guesstimates. The researchers attempted to disaggregate each country by eco-region and forest type in order to acquire detailed data that reflects the variances in forest conditions and land-use changes within each country. For example, the India study divided the country into 27 different regions and 14 different forest types and the Brazilian country study divided the Legal Amazon into 10 sub-regions and 29 eco-regions -- 19 forest types and 10 non-forest types. This approach has resulted in far more detailed examinations of deforestation and forest emissions than have been carried out previously in the seven participating countries. In addition, the process of tracking down the needed information has illuminated key areas with severe data deficiencies. Hopefully, the identification of these trouble spots will lead to the mobilization of the resources needed to fill the gaps.

2.2. The CO-PATH Model

CO-PATH, a spreadsheet model developed at the Lawrence Berkeley Laboratory (LBL) by Makundi *et al.* (1991), provided a common analytical framework for the participating

[2] Neither Myers (1989) nor WRI (1990) have data on emissions or deforestation in China; thus, China is not included in these estimates of the F-7 share of global emissions and deforestation.

institutions. A schematic representation of the model is given in Figure 1. CO-PATH is comprised of two parts, BASIS and FORECAST. BASIS takes detailed physiological data about forests and tracks the conversion of forest areas to four categories of land use (i.e., agricultural land; pastures; harvesting areas; and other uses, such as dams, roads and mining) in order to calculate levels of carbon storage, emissions and uptake for a base year. FORECAST estimates future levels of storage, emissions and uptake, on the basis of past and current rates and types of land-use conversion and the consequent utilization of the affected biomass. Assumptions about the projected use of forest resources also are incorporated into this part of the program. The model uses information from destructive and inventory sampling and remote-sensing data when available.

The choice of a base year for this exercise was dictated by the availability of data. For most of the country studies, 1990 served as the base year. The exceptions were the Mexico and India studies which used 1986. Available evidence suggests that levels of deforestation and emissions did not change significantly in Mexico and India[3] between 1986 and 1990. This study therefore uses the 1986 figures for these two countries when estimating the biome-wide projection for emissions in 1990.

2.3. Description of Main Variables and Definition of Key Terms

For the sake of clarity and consistency, this study sought to define the central activities contributing to carbon emissions and uptake and to identify the key variables needed to develop sounder estimates of carbon flux from changes in forest cover.

Past studies have used the term "deforestation" to describe a wide range of forest-clearing activities. For the purpose of estimating CO_2 emissions, any activity resulting in a change in the amount of carbon stored in a forest should be included. This study focuses on two major categories of forest conversion: **deforestation** and **logging** (see Table 3). **Deforestation** refers to the transformation of former forest lands for the purposes of annual and perennial agriculture, the conversion of forest areas to pastures, harvesting of forests by clear-cutting methods (if the trees are not replanted), and certain other land conversions that lead to the removal of forest cover, such as the construction of dams, mining and destruction by forest fires. **Logging** refers to conversion activities in which only a fraction of the trees are removed from the forest, as is the case for most selective-harvesting activities. Clear cutting, if followed by replanting, also falls under the term logging.[4]

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[3] Uptake in India may have increased between 1986 and 1990 due to the nation's extensive afforestation/reforestation efforts. See section 4.2.

[4] The degree to which the biomass is affected by logging activities varies considerably by place to place.

Figure 1

COPATH: A Spreadsheet Model for Estimating Carbon Flow in Forests

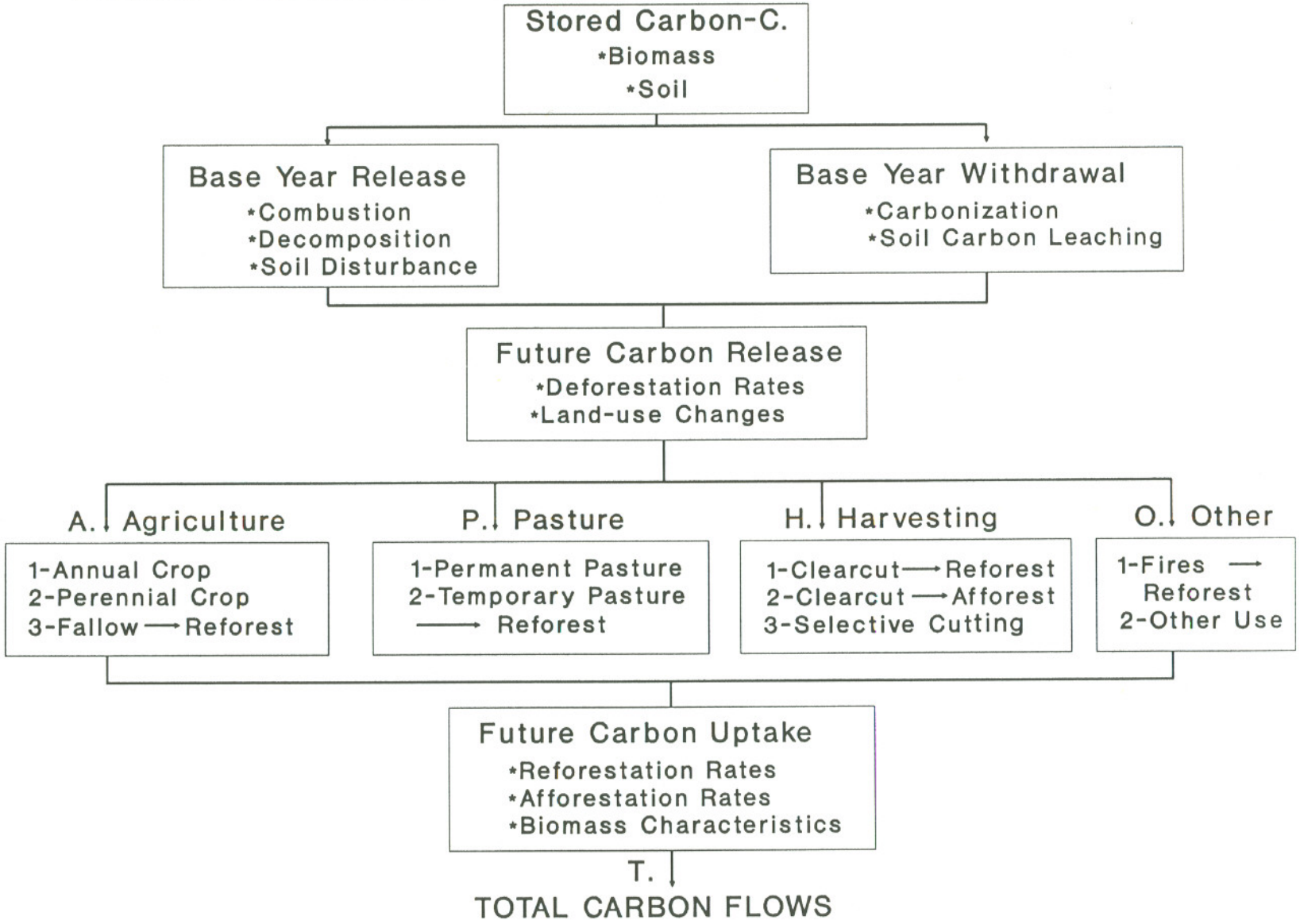

Table 3. Definition of Deforestation and Logging Activities

	Mode of Conversion						
	Agriculture		Harvesting		Pasture	Forest Fires	Development Activities, etc.
	Annual	Perennial	Selective cutting	Clear cutting			
DEFORESTATION	X	X (rubber, coffee, etc.)		X (if not replanted)	X	X	X
LOGGING (includes forest degradation)			X	X (if replanted)			

Hence, the estimates of deforestation presented in this paper refer only to the types of clearing described in the first category. However, the estimates of emissions include both those resulting from deforestation and those resulting from logging. Afforestation refers to the planting of seedlings or young trees in areas where no forests have ever existed and in previously forested areas (e.g. agroforestry, forest plantations, etc.).

The main variables necessary to develop precise estimates of carbon flux from changes in land use fall into the following categories:

1. *Initial Stock of Carbon*: Also known as stored carbon or carbon stock, this term represents the amount of carbon estimated to exist in the ecosystem. Preparing this estimate requires data on total forested area, vegetation types, biomass density and carbon content and soil organic matter.

2. *Rate of Forest Conversion to other Land Uses*: Determining this rate requires detailed information about the activities leading to deforestation and the area under logging (e.g., forest clear cutting, forest degradation and selective harvesting of woody vegetation).

3. *Carbon Release Processes*: Carbon is released through two main processes: decomposition and oxidation. Calculating the rates of release requires detailed information on the forest ecosystems and forest conversion activities.

4. *Carbon Sequestration*: Assessing levels of carbon uptake or sequestration involves data on the extent of afforestation, on the area converted to perennial crops and on the carbon absorption capacity of new vegetation.

5. *Dislocation of Carbon from the Forest Ecosystem to Other Sinks*: Through processes such as erosion and leaching carbon is often transferred from the forest ecosystem to other ecosystems, particularly water bodies.

The key phases of the carbon emission and uptake cycle are illustrated in Table 4. Carbon produced by activities prior to the base year, but generated in the base year (e.g., due to biomass decomposition, etc.) fall into the category of inherited emissions. Emissions resulting from changes in forest cover taking place in the base year are broken down into prompt emissions -- CO_2 emitted in the base year -- and delayed emissions -- CO_2 resulting from base year activities, but generated in years there after. The two latter figures are summed together into committed emissions to represent the gross amount of CO_2 generated by forest activities carried out in a given year over the short- and long-term. Past studies of deforestation and emissions have often failed to incorporate estimates of carbon uptake into their pictures of national and global carbon flux. Various countries, namely India and China, have actively pursued countrywide afforestation programs and thus have greatly increased their sequestration of carbon. This study calculates the inherited uptake, which represents the carbon uptaken in the base year by vegetation growing in the areas that have been deforested in the past. The base

year (prompt) uptake resulting from the growth of forests, perennial agricultural crops for all the F-7 countries and long-term (delayed) uptake for those countries where the necessary data were available are also calculated. The sum of the two last terms constitutes the committed uptake.

Table 4. Definition of Key Terms

Term	Definition
Inherited Emissions	Emissions caused by past forest activities that come on line in the base year (due to the decomposition and oxidation of biomass).
Prompt Emissions	Emissions generated immediately as a result of undertaking a given forest conversion activity.
Delayed Emissions	Cumulative emissions that take place over time as decomposition occurs. Releases of CO_2 due to changes in soil organic carbon, both from forest conversion activities (agriculture, pasture, etc.) and areas under harvesting and afforestation programs, are also included here.
Committed Emissions	Prompt Emissions + Delayed Emissions
Inherited Uptake	Uptake that occurs in the base year from growing forests affected by deforestation and logging in past years and from afforestation activities prior to the base year.
Prompt Uptake	Uptake resulting from annual growth of vegetation (e.g., from agriculture, secondary forests, tree plantations, etc.) and afforestation activities taking place in the base year.
Delayed Uptake	Cumulative uptake that takes place over time due to the growth of vegetation and afforestation activities taking place during the base year.
Committed Uptake	Prompt Uptake + Delayed Uptake
Annual Carbon Balance	Inherited Emissions + Prompt Emissions - Prompt Uptake - Inherited Uptake. Illustrates the flow of carbon in a given year.
Net Committed Emissions	Committed Emissions - Committed Uptake. Quantifies the long-term estimated loss or gain in carbon stock due to forest-related activities occurring in a give year.

The formula for **committed emissions** described above corresponds with the formulas used for estimates made in various other major studies on this topic (Houghton 1991b; Myers 1989; etc.). In addition, the above indicators are used to derive two other important indexes: **annual carbon balance** and **net committed emissions**. The **annual carbon balance** represents the balance between emissions and uptake occurring in the forest sector in the base year. It thus includes both the prompt emissions from deforestation and logging in the base year and the inherited emissions (e.g., from the decomposition of woody biomass) coming from past deforestation. The prompt and inherited uptake are then subtracted to get the annual carbon balance. This indicator can be compared with national estimates of carbon emissions from the energy sector, with estimates of greenhouse gases from agriculture, etc. to provide a broader picture of emission flows in a given year. **Net committed emissions** represent the net long-term change in the carbon content of the original forest cover due to forest conversion activities (i.e., agriculture, pasture, etc.). This index is calculated as prompt plus delayed emissions from current deforestation and logging minus prompt and delayed uptake from the vegetation growing in the deforested or logged areas and on afforested lands. This indicator provides a sense of the sustainability of a country's current forestry activities (i.e., if a country has net positive forestry emissions, it is sequestering more carbon than it is generating and, thus, is maintaining sustainable forest management practices).

3. FOREST RESOURCES

The term "forest" can encompass a vast array of ecosystems, from arid plains with sparse patches of trees to densely treed moist tropical woodlands. Most of the F-7 studies focused on the entire national stock of forests of all types -- tropical, temperate, subtropical, etc. The one major exception is the Brazil study, which only includes the forests (and *cerrados*) located in the Amazon region. In the analysis of Thailand and India, forests are defined as wooded areas with over 10 percent crown cover. Forests in the Mexico study refer to all closed forests. In China, Indonesia and Malaysia, the study includes closed, open and fallow forests. The more detailed differences in forest definitions can be found in the individual country studies. In most of the countries considered here tropical forests dominate; as Table 5 shows, however, China and Mexico are two major exceptions to this rule. Tropical forests constitute only half of all Mexican closed forests. Although less than 2 percent of all Chinese forests are moist tropical forests, more than half are subtropical forests. One of the contributions of this work is the quantification of emissions emanating from non-tropical forests in China and Mexico, an area which commonly has been overlooked by past studies.

The countries included in this study embrace a wide range of cultures, ecosystems, political and economic structures and demographic characteristics. These factors all influence the role of the forests within a given country and must be considered in order to shape effective responses to forest-related problems. The diversity of these seven countries highlights the importance of developing individually molded strategies for restraining deforestation.

Table 5 highlights the widely ranging characteristics of the F-7 group of countries regarding population, country size, forested area and per capita forest endowments.

Table 5. Population, Land Area and Forest Resources

Country	Base Year	Population (millions)	Total land area (10^6 ha)	Total forest area (10^6 ha)	Forested area as a share of total land area (%)	Forest area per capita (ha)	Main forest type
Brazil[a]	1990	140	845.7	390[a]	46.1	2.79	Moist tropical
China[b]	1990	1130	960.0	120[b]	12.5	0.11	Subtropical, temperate
India[c]	1986	843	328.8	64[c]	19.5	0.08	Mixed deciduous
Indonesia[b]	1990	179	190.8	109[d]	57.1	0.61	Dipterocarp
Malaysia[b]	1990	18	33.0	19[e]	57.6	1.06	Dipterocarp
Mexico[d]	1986	81	196.7	51[f]	25.9	0.63	Tropical, temperate
Thailand[e]	1990	58	51.1	16[e]	31.3	0.28	Tropical evergreen, deciduous
Total	--	2449	2606.1	769	29.5	0.31	

Notes: a. Refers only to those forests (and *cerrados*) located in the Amazon region.
b. Includes closed, open and fallow forests.
c. Forests defined as woodlands with more than 10 percent crown cover.
d. Forests defined as all closed forests (FAO definition).

Forest area per capita illuminates some other issues that often arise in international discussions on deforestation. Particularly in the case of countries that rely heavy on the domestic use forest products, such as for fuelwood, this indicator provides a general sense of the availability of forest resources (although, of course, the availability of resources is largely related to the relative location of the wood-consuming members of the population and the forests along with many other factors). Despite their large forest tracts, China and India have particularly low levels of forest per capita, at 0.11 and 0.08 hectares per capita respectively. Brazil boasts 35 times more forest than India on a per capita basis (2.79 ha/capita).

When attempting to determine carbon emissions from deforestation, it is essential to recognize the different characteristics of the various forest types. As shown in Table 6, the average density of the biomass found in the different countries' forests varies considerably. Tropical moist forests tend to have the most biomass per unit area, whereas temperate forests have less, although the soil carbon in temperate ecosystems is higher than in tropical forests. Hence, the density of biomass is far greater in Brazil and Indonesia than in countries where closed moist forests are less prevalent (Table 5). Mexico has a substantially lower estimate of dry biomass per hectare than the other countries because tropical forests constitute only 50 percent of the total forest area and a significant fraction of tropical forests are deciduous forests with low biomass densities. Because subtropical forests dominate in China, its forests are more dense than those in Mexico. A large proportion of Malaysia's woodlands have been logged over; as a result, the biomass density of Malaysian forests is 30 percent lower than Indonesian forests even though both countries have similar forest types. The CO_2 implications of biomass density are considered in the section on carbon emissions and uptake.

Table 6. Biomass Density Estimates (tonnes of dry biomass/ha)

Country	Biomass (tonnes of dry biomass/ha)			Carbon content of biomass (tC/ha)
	Above-ground	Below-ground	Total	
Brazil[a]	309	73	382	191
China	233	41	274	137
India	131	169[b]	300	150
Indonesia	354	28	382	191
Malaysia	223	46	269	135
Mexico	114	36	150	75
Thailand	270	31	301	151

Notes:
a. Refers only to those forests (and *cerrados*) located in the Amazon region.
b. Includes soil organic carbon. This number is being refined to be more consistent with the others presented in this table.

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Lawrence Berkeley Laboratory

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Please review the paper for:

A. CONTENT	No	Yes	Good
1. Is the abstract succinct and complete?	0	X	0
2. Are the assumptions reasonable?	0	X	0
3. Is it original work?	0	X	0
4. Is the technical work accurate?	0	X	0
5. Are the results substantiated?	0	X	0
6. Are conclusions clearly stated?	0	0	0 — could be improved

If you know of any closely-related publications not referenced in this paper, please list as part of comments.

B. STYLE			
1. Organization — could use a conclusion section	0	0	0
2. Writing	0	0	X
3. Graphics → need a lot of work!			

C. OVERALL EVALUATION			
1. Was the paper worth writing?	0	X	0
2. Is it worth publishing?	0	X	0

D. ADDITIONAL COMMENTS:

This is generally a good paper with interesting results, I have made several suggestions in the text to maintain consistency of units throughout and to clarify the subject matter. A few other inconsistencies found: graphics generally poor — but all in all it does make a good paper. RR

Reviewers Signature Ron Ritschard Date 4/2/92

Please return this sheet to: JAYANT SATHAYE by March 31st, 1992
DATE

Address 90-4000 Phone 486-6294

Also — if funding can be found from EPA or others, I would be interested in providing remotely-sensed data analysis + GIS data base for one or more of the 27 countries. We could start w/ one to build the system & demonstrate

Date 032392
LBL No. 32119

Building Energy Analysis Group
Lawrence Berkeley Laboratory

ENERGY ANALYSIS PRE-PUBLICATION REVIEW FORM

Reviewer OMAR MASERA

Paper Title CARBON EMISSIONS AND SEQUESTRATION IN TROPICAL FORESTS

Authors MAKUNDI & SATHAYE

Intended destination:

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Please review the paper for:

A. CONTENT	No	Yes	Good
1. Is the abstract succinct and complete?	0	X	0
2. Are the assumptions reasonable?	0	X	0
3. Is it original work?	0	X	0
4. Is the technical work accurate?	0	X	0
5. Are the results substantiated?	0	X	0
6. Are conclusions clearly stated?	0	X	0

If you know of any closely-related publications not referenced in this paper, please list as part of comments.

B. STYLE			
1. Organization	0	X	0
2. Writing	0	X	0
3. Graphics			

C. OVERALL EVALUATION			
1. Was the paper worth writing?	0	X	0
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4. CHANGES IN FOREST COVER

4.1. Deforestation and Logging

Deforestation has already led to a major decline in forest area in most of the F-7 countries relative to the extent of forest area present in pre-industrial and pre-agricultural times. Indonesia's forest area dropped from an original estimate of 170 million hectares (ha) to 119.7 million hectares by 1982. Just in the last decade, substantial deforestation has occurred; as of 1990, Indonesia's forest cover had fallen to 109 million hectares. A similar trend can be seen across the F-7 countries. India has less than half of its original forest cover, and about one-fifth of the forests standing today are extremely degraded. Malaysia and Thailand each have an estimated 63 percent of their original forest cover. Endowed with vast forest resources, Brazil still maintains about 90 percent of its original forested area.

Table 7 presents the absolute area deforested in each of the F-7 countries in the base year. Brazil dominates the list. Deforestation rates range from a low of 0.24 million hectares/year in Thailand to Brazil's high of 1.38 million hectares/year. The share of deforestation in total forested area is also notable -- spanning from 0.4 percent in Brazil to 2.4 percent in Malaysia.

Table 7. Deforestation[a] in F-7 Countries, Base Year

Country	Base Year	Area deforested (10^6 ha)	Deforested area as a share of total forest area (%)
Brazil[b]	1990	1.38	0.4
China	1990	0.69	0.6
India	1986	0.50	0.8
Indonesia	1990	1.09[c]	1.0
Malaysia	1990	0.46	2.4
Mexico	1986	0.67	1.3
Thailand	1990	0.24	1.5
Total	---	5.02	0.7

Note: a. Deforestation does not include degradation from logging (see methodology section). However, the estimates of emissions presented later in this paper stem both from the deforestation activities quantified in Table 7 and from logging.
b. Refers only to forests (and *cerrados*) located in the Amazon region.
c. Includes area cleared by selective logging.

An examination of the literature indicates that rates of deforestation have declined in a number of the countries since the early- and mid-1980s (IPCC 1992). The 1990 estimate for

Indonesia, 1.09 million hectares, is slightly lower than the annual figures for 1982-1989, which averaged about 1.35 million hectares. In an even more dramatic example, the 1990 deforestation estimate for Thailand of 235,000 hectares is equivalent to about half of estimates from earlier in the decade; this change stemmed from the Thai government's implementation of the logging ban in 1988. In Brazil, Amazon forest loss averaged 22 million hectares/year between 1978 and 1988, fell to 19 million ha/yr in 1989 and dropped further to 13.8 million ha/yr in 1990 (the base year of this paper). By 1991, Amazonian clearing had declined by 20 percent, to 11.1 ha/year.

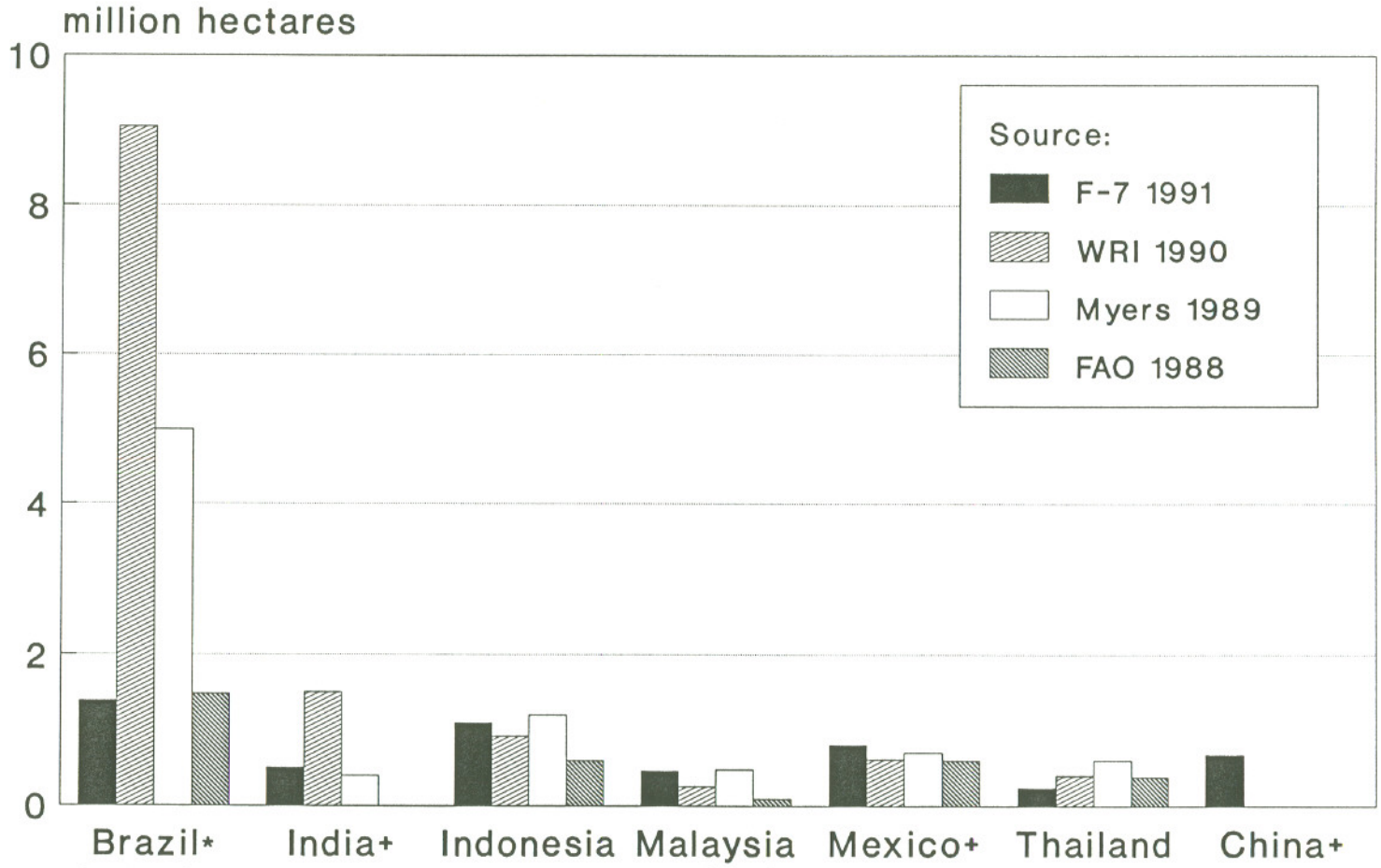
Figure 2 compares the F-7 estimates of deforestation with estimates from Myers (1989), WRI (1990) and FAO (1988). Some of the discrepancies in the estimates of deforested area reported by different sources can be attributed to inconsistencies in the years for which each calculation was made; the F-7 data is from 1990, Myers's data is from 1989 and WRI's from 1987. The FAO estimates are particularly low, because they represent rates from the early- to mid-1980s, prior to the period when deforestation accelerated in many countries. The most widely varying estimates are for Brazil. The most striking of the F-7 results, the estimate of deforestation in Brazil stands at one-sixth of WRI's estimate and one-third of Myers's estimate. In the case of the WRI estimate for Brazil, the choice of a base year is somewhat misleading, because 1987 had far more deforestation and burning due to unusually dry weather conditions and a strong reaction to political debates over the possibilities of redistributing forest areas then possessed by cattle ranchers as part of an agrarian land reform program. The Myers and WRI calculations both suffer from certain methodological problems (see Fearnside 1992 for detailed explanation). Similarly, the F-7 study of Thai forests found considerably less deforestation than past studies. In contrast, the F-7 calculations for Mexico exceed all three of the others, primarily because deforestation of Mexico's non-tropical forests was included in the F-7 report. Myers, FAO and WRI all excluded China from their surveys. This study found that substantial deforestation occurs in China each year. In the case of Indonesia, India, and Malaysia, the F-7 estimates fell somewhere in the middle of range of the comparison studies.

The primary activities responsible for deforestation tend to be consistent within continents, although the mix of activities varies significantly from country to country as do the forces driving the various activities. In Latin America, conversion to pasture is the dominant mode of deforestation (Table 8); government subsidies offered to cattle ranchers and policies promoting land speculation continue to propel these types of activities. Cattle-ranching activities lead to about three-quarters of all clearing in Brazil and about half of all clearing in Mexico. Much of the fallow agricultural land in Brazil is ultimately abandoned to pasture, thus adding to the land conversion for this purpose. The high share of clearing for pasture is relatively new to Mexico, having emerged mainly over the past 25 years. Forest fires also make a substantial contribution to Mexican deforestation. Agriculture, harvesting and development projects each account for about a third of the remaining deforestation in Brazil.[5]

[5] Brazil's future development strategy, which includes a plan to flood 10 million hectares by the year 2010 (Johns 1988) to create hydroelectric dams and timber harvesting activities that could affect up to 50 million hectares of forest, could lead to a large shift in the shares of the respective clearing activities in the future.

Figure 2

Cross-Study Comparison of Deforestation Estimates for the F-7 Countries



Base year and notes: F-7 study - 1990, except India and Mexico (1986), see table 5 notes for scope; WRI - Av. annual figure for 1980s, only closed forests, except Brazil (open & closed); Myers - 1989, only closed tropical forests; FAO - av. annual fig. for the early-to-mid-1980s, open and closed forests. + Legal Amazon * Includes tropical and temperate forests

Conversion of forest land for agricultural and harvesting purposes dominates throughout most of Asia. In Thailand, India and Indonesia, shifting cultivation by small land owners accounts for the bulk of all deforestation. In China about three-quarters of all forest clearings can be attributed to harvesting, primarily through clear-cutting methods. Malaysia exports large quantities of wood products from the logging of primary and secondary forests.

Many Asian countries also carry out extensive logging activities. In both Indonesia and India, logging accounts for about 10 percent of all clearing. Logging is highly selective in Indonesia (the intensity cannot legally exceed 25 percent of the stemwood inventory). In India and Thailand, the culling of forest resources for fuel and other wood products are the main forms of harvesting. While the government of Thailand instituted an official ban on logging in 1988, there is evidence of illegal logging taking place. In addition, approximately 7.8 million Thais live in the official forest reserves and rely heavily on the forest for sustenance. Harvesting accounts for the major portion of all deforestation in China and Malaysia. While Malaysian loggers employ selective cutting, their harvesting methods tend to be extremely wasteful and typically the forests require long recovery periods. Malaysia also has converted large tracts of forest to agricultural crops, such as rubber, oil palm, cocoa and coconut. The clearing of forests for pasture is uncommon in Asian countries, with the sole exception of India, where conversion to pasture accounts for about one-fifth of all clearing.

While no African countries have been included in this report, the preliminary results from the Nigeria country study and other sources (Myers 1980,1989; FAO 1981,1988; White 1983) indicate that conversion to agriculture is the major forest-clearing activity in Africa, followed by harvesting.

Table 8. Estimated Contribution of Major Conversion Activities to Deforestation and Logging[a] (%), Base Year[b]

Conversion Activity	Country					
	Brazil[c]	China	India	Indonesia	Mexico	Thailand
Agriculture	10	16	63	83	13	59
Pasture	72	0	21	0	49	6
Harvesting[d]	8	77	12	9	4	26
Other	10	7	4	8	34	10
Total[e]	100	100	100	100	100	101

Notes:
a. The shares for Mexico do not include logging activities.
b. Shares for Malaysia are not available.
c. Refers only to those forests (and *cerrados*) located in the Amazon region. Logging is excluded from these shares (taken from Browder (1988).
d. Areas under selective-cutting are adjusted to according to the intensity of biomass removal.
e. Numbers do not all add up to 100 percent due to rounding.

4.2. Afforestation

As a means for preventing the growth of forest-related emissions, sustainable management of natural forests and forest protection are the optimal methods. However, the development of agroforestry and tree plantations on previously unforested lands can provide countries with options to reduce the atmospheric concentration of carbon dioxide originating from human activities. The biomass density and carbon accumulation of new forests can exceed those of the initial natural vegetation depending on the silvicultural practices. In addition, afforestation projects can be designed to offer gainful employment to rural peasants who formerly earned their living through activities resulting in deforestation.

Afforestation has taken place, at least to a limited extent, in all of the F-7 countries (Table 9). These programs typically have been spurred by the rising demand for forest resources and/or the need to control erosion and improve agricultural production through the development of large shelter belts. In rare instances, such as the case of India, powerful environmental movements have led to the development of policies promoting afforestation.

Table 9. Total Afforested Area (Forest and Agricultural Plantations) through the Base Year

Country	Afforested Area (10^6 ha through the base year)
Brazil[a]	7.0
China	30.7
India	11.5
Indonesia	4.2
Malaysia	4.7
Mexico	0.2
Thailand	2.3
Total	60.6

Notes: a. Refers to the total estimated area under forest plantations in the country (taken from Freitas (1990).

The character of the afforestation programs underway in various countries differ. China's program is unusual because it involves the reconversion of large areas formerly devoted to other land uses to forest land. Afforestation activities in the countries of Southeast Asia (Malaysia and Thailand) typically are dominated by the cultivation of agricultural perennials, such as rubber, oil palm, cocoa and coconut plantations. In contrast, Brazil and Indonesia have

large industrial and non-industrial forest plantations, mainly consisting of eucalyptus, teak, and pines, as do India and China.

China has initiated the most extensive afforestation program in the world; as of 1990, the country had a total of 30.7 million hectares of planted forests. India's afforestation process, accelerated by the enactment of the Forest Conservation Act of 1980 which was aimed at stopping forest clearing and degradation through a strict, centralized control of land-use rights, resulted in a total 11.5 million hectares as of 1986; approximately 5.6 million more hectares were afforested between 1986 and 1989, raising the total planted area to 17.1 as of 1989. Indonesia has 4.2 million hectares afforested, from which 69% is occupied by forest plantations. In Malaysia, 96% of the 4.7 million hectares afforested consist of perennial crops (mainly rubber and palm oil).

The extent of the afforested areas is far less notable in the other countries. Brazil does have plans to substantially increase its afforestation activities in the future, largely as a means for ensuring the availability of forest products. The current plan would increase the area under forest plantations to 16 million hectares by the year 2000. Mexico has only devoted a limited land area to tree planting; as of 1990, only 146,000 hectares of Mexican land was under afforestation programs. However, future plans for Mexico's forestry sector include the goal of afforesting 100,000 hectares per year between 1992 and 2000.

The cumulative area that has been afforested in the F-7 countries totals about 62 million hectares. While forest plantations have gained popularity and a number of countries have plans to increase their efforts in this direction, the total area afforested still represents less than 10 percent of the cumulative loss of tropical forests. In addition, the extent to which the newly planted trees are compensating for tree clearing is not even across regions. The FAO estimated the ratio of deforested to afforested areas to be 4:1 in Asia, 10:1 in South America and 35:1 in Africa (FAO 1988).

5. CARBON EMISSIONS

Estimates of carbon stocks and emissions from forest clearing have been controversial over the years due to uncertainties about the magnitudes of the contributing factors (i.e., rates of deforestation and afforestation and estimates of other parameters affecting the carbon cycle). The use of different methodologies have also led to divergent estimates.

The main variables necessary for calculating carbon emissions from deforestation and logging were discussed in the methodology section. One of the key parameters for this computation is the carbon stock (or carbon storage) of the forest. This term basically represents all of the carbon existing in vegetation, soil, forest litter, etc. The changes in this variable over time have implications about the sustainability of a country's land-use practices.

The estimated stock of carbon contained in the forests of the F-7 countries is shown in Table 10. The total, 159 billion tonnes of carbon, exceeds the IPCC's (1992) estimate of the amount of anthropogenic carbon emissions (from all sources) generated globally each year by a factor of twenty. As is the case for forest area and deforestation per capita, figures for carbon stock per capita have relevance in global discussions on national obligations in regards to the forest sector.

Table 11 provides estimates of prompt, delayed and committed carbon emissions and uptake for the base year. In China, India and Mexico, the bulk of all emissions resulting from deforestation and logging that took place in the base year were released during the base year. In contrast, in Brazil, Indonesia, Malaysia and Thailand the majority of the emissions were delayed. The differences in the proportion of emissions released immediately and those released over the long term stem from a number of factors, including the assumed biomass decomposition periods by forest types, modes of deforestation and the use of the forest products. For example, countries like India where a large number of people use wood from the deforested areas for fuel may experience particularly high releases of prompt emissions.

Table 10. Carbon Stock in the Base Year

Country	Carbon Stock (GtC)	Carbon Stock per capita (tC)	Committed Emissions as a Share of Carbon Stock (%)
Brazil[a]	87	620	0.3
China	20	18	0.7
India	10	11	0.6
Indonesia	29	161	0.6
Malaysia	3	188	0.2
Mexico	7	86	0.8
Thailand	3	48	0.2
Total	159	65	0.5

Notes: a. Refers only to those forests (and *cerrados*) located in the Amazon region.

Table 11. Carbon Emissions and Uptake, Base Year (MtC)

Country	Carbon Emissions (MtC)				Carbon Uptake (MtC)				Annual Carbon Balance (MtC/year)[a]	Net Committed Emissions (MtC)
	Inherited[a] (1)	Prompt (2)	Delayed (3)	Committed (4) = (2) + (3)	Inherited[b] (5)	Prompt (6)	Delayed (7)	Committed (8) = (6) + (7)	(9) = (1) + (2) - (5) - (6)	(10) = (4) - (8)
Brazil[c]	265	120[d]	176[d]	296	74	2.6[e]	23.4	26.0	308	270
China[f]	62	73	62	135	111.4	9.4	43	52.4	14	83
India	26	38	26	64	68.8	n.a.	120	120.0	-5	-56
Indonesia	98	84	98	182	57	1.7	90.4	92.1	123	90
Malaysia	29	24	29	53	28.8	1.83	65.3	67.1	22	-14
Mexico	26	28	26	54	3.2	0.3	8.2	8.5	51	46
Thailand	32	24	29	53	14.3	0.4[f]	n.a	0.4	41	53
Total	538	391	446	837	357.5	16.23	350.3	366.5	554	472

Notes: a. For Brazil, India, and Thailand inherited emissions were calculated using historic average deforestation rates for the past ten years. For the rest of the countries it was assumed that past deforestation is approximately equal to deforestation in the base year.
b. For Brazil, Indonesia, Mexico, and Thailand inherited uptake was estimated assuming a 10 year growth of the vegetation replacing the deforested areas (the dominant modes of forest conversion are agriculture and pasture in these countries, see Table 8) and using the same average uptake per hectare per year as in the base year. The uptake from all afforested/reforested areas growing in the base year was added to the inherited uptake from areas deforested.
c. Emissions refers only to those forests (and *cerrados*) located in the Amazon region; inherited uptake includes the total area under plantations in the country; prompt and delayed uptake figures do not include forest plantations.
d. The numbers here were derived using the same prompt:delayed ratio as an earlier estimate.
e. We assume a 10-year growing period of the secondary vegetation to reach biomass equilibrium (committed uptake).
f. The base year for China is 1988 here.
g. The figure doesn't include uptake from forest plantations.

Over 35 percent of total committed emissions from the F-7 countries were generated from the Brazilian Amazon. Whereas past studies have not calculated committed emissions from China, this report indicates that in 1990 Chinese forests generated 135 MtC, or just under half the quantity emitted from the Brazilian Amazon and about 16 percent of the F-7 total. Malaysia, Mexico and Thailand accounted for the smallest relative shares -- about 6 percent each.

Figure 3 compares the F-7 estimates of committed emissions with estimates prepared by other authors. The most striking disparities are in the case of Brazil. The F-7 estimates of forest-related carbon emissions from Brazil are 76 percent lower than the WRI estimate and 35 percent lower than the Myers estimate. The differences between the emissions figures from the three sources, while substantial, nonetheless are less pronounced than the differences in the estimates of deforested area discussed previously. The reason is the following: this study relies on a biomass estimate that is 40 percent higher (recalculated using LANDSAT imagery and destructive sampling data) than the previous best estimates (Fearnside 1990b) used in the Myers, WRI and FAO reports. If the updated data on biomass density were used to calculate emissions using estimates of deforestation from WRI, FAO and Myers, the resulting CO_2 calculation would be substantially higher than the one reported here.

The F-7 committed emissions figures for Mexico, Thailand, India and Malaysia all fall somewhere in between the estimates from the other three sources. In all four countries, the differences in the figures primarily stem from varying estimates on types of forests, deforestation rates, biomass density and soil carbon content.

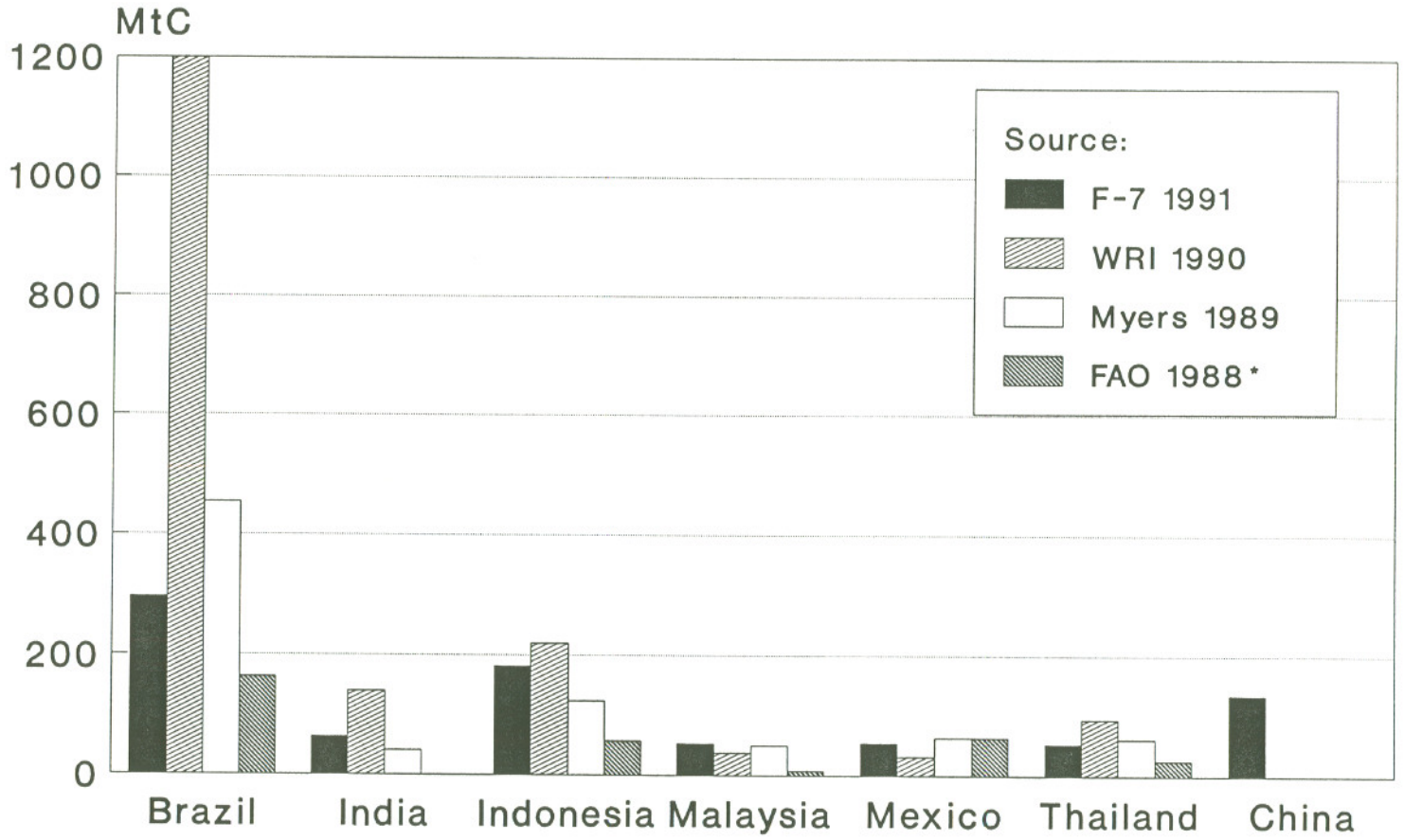
Excluding emissions from China, which were not incorporated into the WRI or Myers report, the forest-related carbon from the remaining six countries totaled 795 million tons according to Myers and 1724 million tons according to WRI (See Table 2). In contrast, the F-7 estimate for committed emissions from these six countries stands at 702 million tons. When the China estimates are included, the F-7 estimate rises to 837 million tons of carbon, still equalling less than one-half of WRI's calculation. While declining rates of deforestation in the countries examined may account for some of the dissimilarities, the more accurate assessments of deforested area and more precise information about the other key variables incorporated into the F-7 studies account for the bulk of the difference. The F-7 study also considers temperate forests in Mexico and some open forests in India and various other countries, neither of which are included in any of the other reports. If emissions from these forests were removed from the F-7 totals, the difference between the F-7 results and those from the three other studies would be even more striking.

6. CARBON UPTAKE

The combined estimates of inherited and prompt uptake for China, India and Malaysia reflect the success of these three countries' far-reaching afforestation projects (Table 11). At 121 MtC/yr, China's inherited and prompt carbon uptake overshadows levels of sequestration in the other countries studied. Notable carbon sequestration also took place in Brazil, India, Indonesia and Malaysia, where tree plantations, agroforestry and continued forest growth led to

Figure 3

Cross-Study Comparison of Committed Emissions from Deforestation and Logging



Base Year: F-7 study - 1990; WRI - 1987; Myers - 1989; FAO - annual average rate for the early-to-mid-1980s.

* Calculated using FAO estimates of deforested area and Houghton's estimates of carbon density (in Myers 1989).

combined inherited and prompt carbon uptakes of 77 MtC/yr, 69 MtC/yr, 59 MtC/yr and 31 MtC/yr respectively. As Table 11 shows, uptake was far lower in Thailand and Mexico. The ratio of committed emissions to uptake in this last country largely reflects the nature of the forest clearing taking place in that region. Conversion to pasture results in complete tree removal, typically through burning; vegetative regrowth represents only a minor fraction of the original forest biomass. The total uptake in the base year in the F-7 countries reaches 374 MtC/yr.

The uptake estimates have a significant impact on the assessment of the net emissions generated by each country. The annual carbon balance for the F-7 countries drops by 34 percent with respect to committed emissions, from 837 MtC/yr to 554 MtC/yr, when prompt and inherited carbon sequestration are taken into account. Net committed emissions, which account for committed uptake, are 472 MtC, 46 percent lower than committed emissions (Figure 4). The large difference between committed emissions, annual carbon balance, and net committed emissions arises from the important uptake in countries like China, India, Indonesia, and Malaysia. Despite committed emissions totaling 135 MtC/yr, China has an annual carbon balance of only 14 MtC/yr due to its combined inherited and prompt carbon uptake of 121 MtC (Figure 5). India is the sole example among the countries represented in this study of a country with forests that actually sequester more carbon than they emit in the base year; despite annual committed emissions of 64 MtC, India has an annual carbon balance of -4.8 MtC/yr. Net committed emissions are negative for both India (-56 MtC) and Malaysia (-14 MtC).

7. F-7 EMISSIONS AND THE GLOBAL PICTURE

The results derived from each of the detailed case studies can be used to construct a more accurate picture of the quantity of anthropogenic carbon emitted from the combustion of fossil fuels and land-use changes in each of the F-7 countries. In addition, the new estimates of carbon emissions from deforestation and logging can be supplemented with existing estimates of forest-related emissions for the rest of the world to provide a more precise calculation of global forestry emissions.

7.1. Emissions from Energy and Forestry

Fossil fuel combustion and forestry are the two major anthropogenic sources of CO_2 emissions. In the seven developing countries examined here, energy emissions (663 MtC/yr) are 20% larger than forestry emissions (554 MtC/yr, annual carbon balance). Figure 6 combines estimates of annual carbon balance from forestry for the F-7 countries with estimates of emissions from energy use drawn from a compatible study carried out by the International Energy Studies Group at the Lawrence Berkeley Laboratory (see Sathaye and Ketoff 1991 for more detail). The relative contributions of energy use and deforestation to total emissions vary significantly from country to country. Brazil and Indonesia both rely heavily on clearing and exploiting extensive tracts of forest lands for economic activities. Indonesia has relatively low levels of commercial energy consumption per capita, and Brazil relies heavily on hydropower, a non-carbon intensive energy source. As a result, deforestation accounts for a far higher share of emissions than does energy use in both of these countries. In contrast, the heavy consumption

Figure 4

Comparison of Annual Carbon Balance and Committed Emissions, F-7 Estimates, 1990

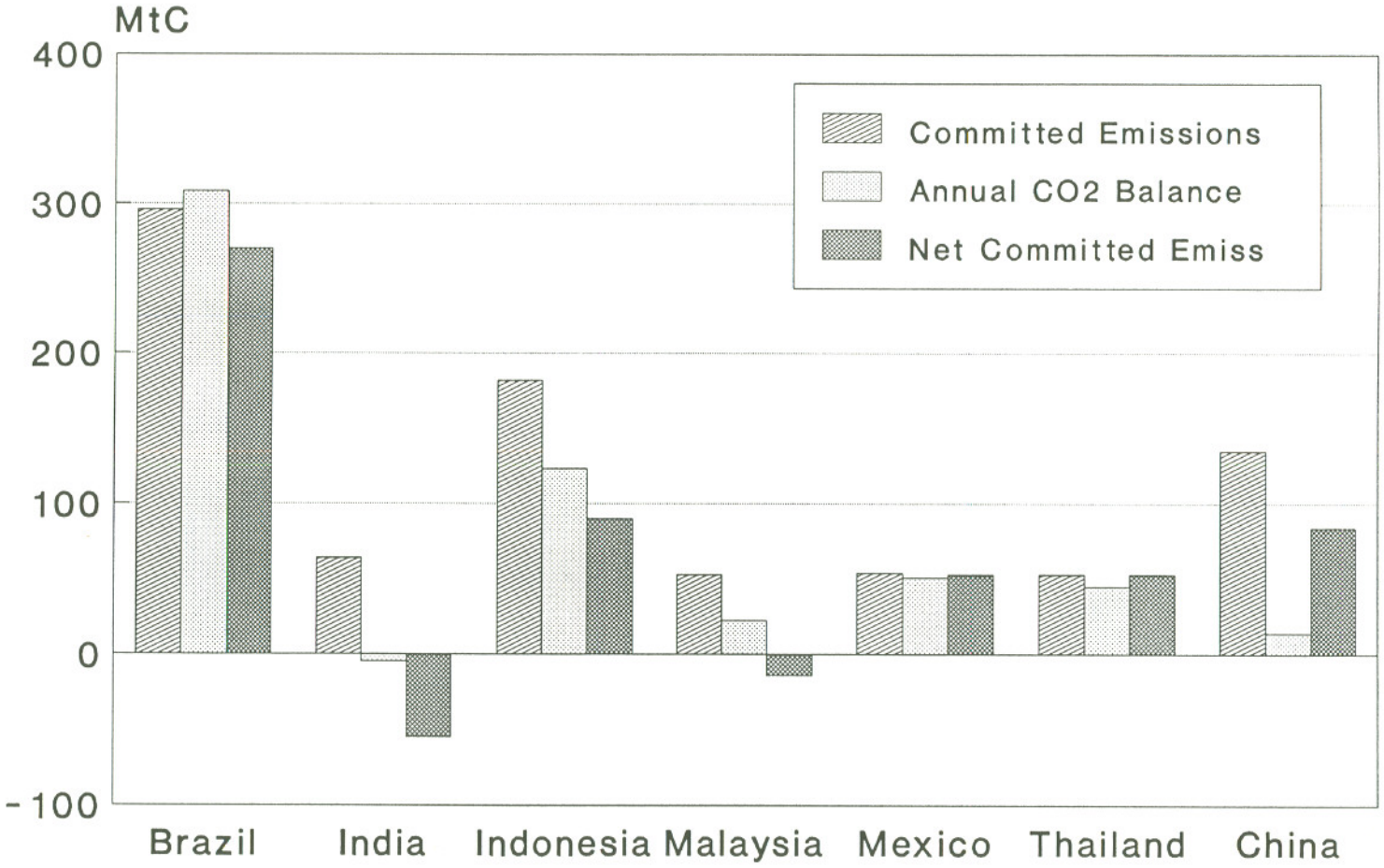
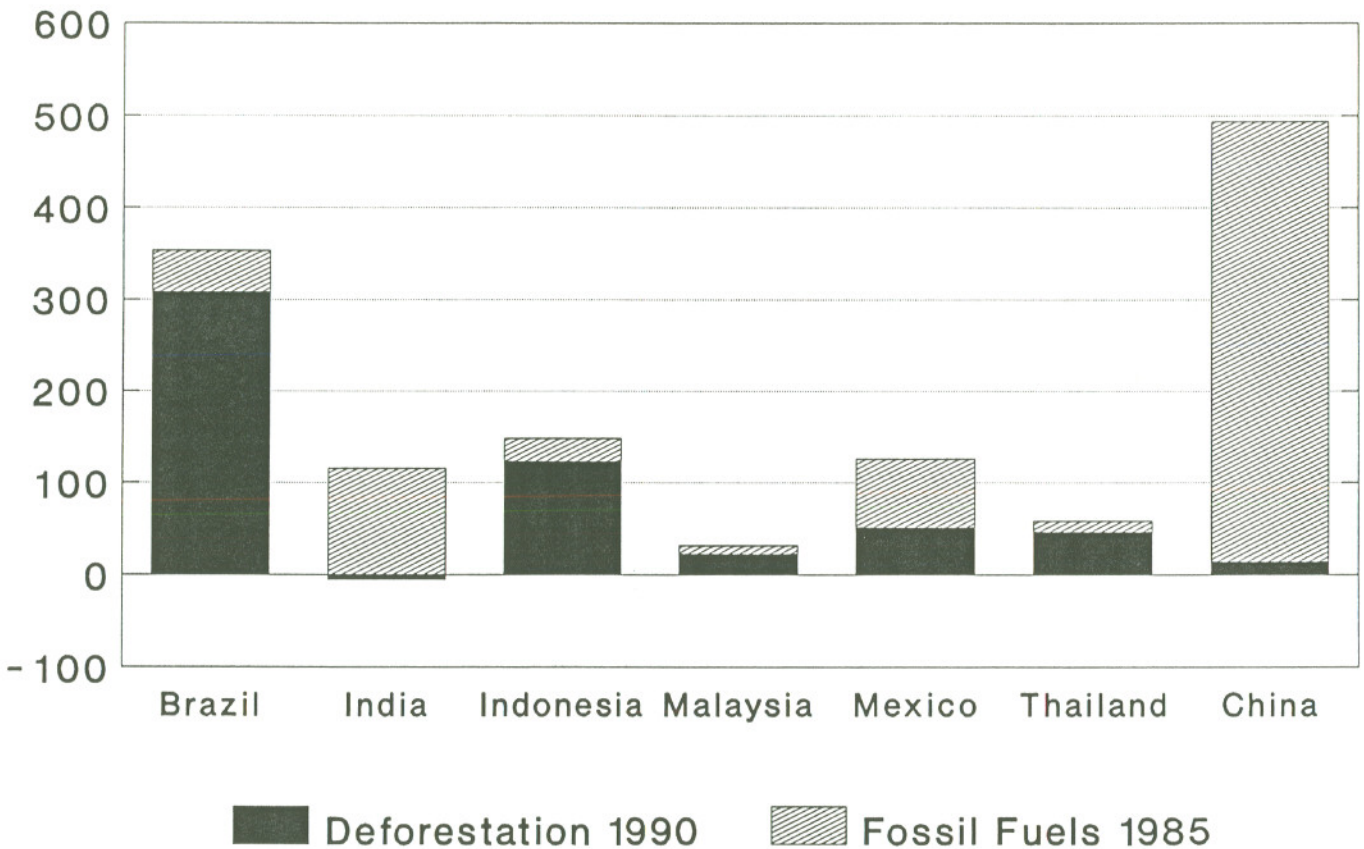


Figure 5

Carbon Emissions from Energy & Forestry in the F-7 Countries



Sources: Forestry - F-7 1991; Energy - Malaysia - LBL database; Thailand - TDRI 1990; Others -Sathaye 1991.

Forestry emissions correspond to the annual carbon balance

of carbon-intensive coal in China and India leads to far higher emissions of CO_2 each year than does deforestation.

As a share of the global total, the quantity of fossil fuel-related emissions generated by these seven countries equals about 12-15 percent of all CO_2 emitted as a result of commercial energy use worldwide[6] -- a stark contrast to the F-7 countries' predominant contribution to global forestry emissions. Excluding China, which alone generated almost two-thirds of the energy-related CO_2 from the F-7 countries, the remaining countries account for only 5-6 percent of global energy emissions.

7.2. Implications for a Global Assessment

The seven countries examined in this work account for most worldwide emissions from logging and deforestation. Thus, the refined estimates contained in this report represent a major step towards achieving a far sounder global estimate of forest-related emissions.

A reliable assessment of worldwide emissions will require similar country-by-country studies to be carried out in the remaining countries where forestry emissions are generated. In the absence of detailed country studies for the rest of the world's tropical countries, this paper provides a provisional global estimate of carbon emissions from the forestry sector. The global estimate is calculated by taking the F-7 estimates for the seven countries examined here and then using an adjusted figure for the rest of the world based on Myers's (1989) estimates.
According to Myers, the F-7 countries, excluding China, account for just over 57 percent of global emissions from closed tropical forests (i.e., 0.795 GtC vs 1.4 GtC, see Table 2). In this calculation we assume: (a) that the proportion of F-7 countries in global emissions from closed forests is the same as that estimated by Myers (1989) and (b) that the F-7 countries also represent 57% of global emissions from open and fallow forests; therefore these countries are estimated to account for 57% of global emissions from all deforestation. We then replace our figures for the F-7 countries (702 MtC for closed and open forests-- excluding China[7]) for Myers' and add the adjusted contribution from the rest of the World. As a result, our estimates for global emissions --including China-- are about 40% lower than Myer's estimate.

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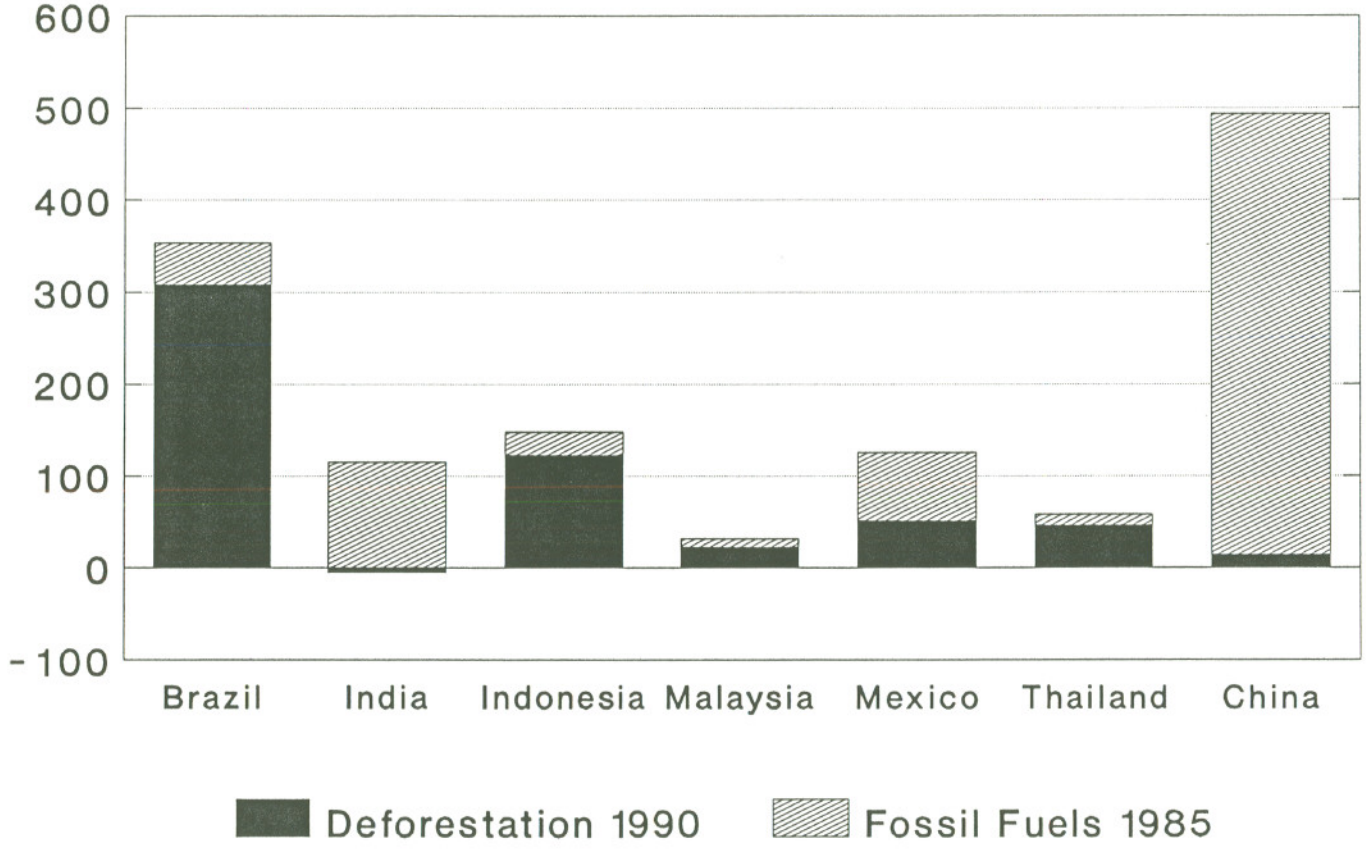
[6] Based on an estimate of global CO_2 emissions from fossil fuel burning of 5.2-6.2 GtC made by the U.S. Congress, Office of Technology Assessment (1991).

[7] Many of the F-7 country studies include emissions from both closed, open and fallow forests. Therefore, the emissions from the F-7 countries presented in this study should be compared to global estimates of carbon emissions from deforestation as opposed to emissions from closed forests alone.

Figure 6

Carbon Emissions from Energy & Forestry in the F-7 Countries



Sources: Forestry - F-7 1991; Energy - Malaysia - LBL database; Thailand - TDRI 1990; Others -Sathaye 1991.

Forestry emissions correspond to the annual carbon balance

The resulting estimates place worldwide committed emissions from all forests -- open and closed -- at 1.4 GtC/year. An examination of the main factors used in estimating the figures for each of the participating countries and the associated uncertainties indicates an imprecision range of 20 percent. These estimates are lower than many previous estimates, and the range is narrower (Table 13).[8]

Table 12. Estimates of Global Forestry Emissions, 1989-90, GtC/year

Source	Committed Emissions (GtC)
From F-7 Countries - China	0.702[a]
From China	0.135
From the Rest of the World	0.563
F-7 Global Estimate:	1.400

Notes: a. This estimate does not include emissions from open forests in Brazil and Mexico.

Table 13. Comparison of Estimates of Global Committed Emissions from Forest Clearing

Source	Estimate of Global Committed Emissions from Open and Closed Forests (GtC)
F-7 (1991)	1.4 ($\pm$0.3)
Myers (1989)	2.0 - 2.8
Houghton (1991b)	1.1 - 3.6
IPCC (1990)	0.6 - 2.6

[8] If "net committed emissions" as opposed to "committed emissions" are used in the calculations, the estimate of global carbon emissions will be even lower.

8. AREAS OF FUTURE RESEARCH AND CONCLUSIONS

8.1. Areas of Future Research

The country level approach taken in this study has allowed for a more detailed evaluation of the forestry emissions produced by seven countries that make key contributions to global emissions of carbon dioxide. Individual papers on each of the F-7 countries currently are being refined. Some of the studies project future emissions and uptake from the forestry sector under a range of different scenarios. In the future, as the tools necessary for calculating these figures improve and even more detailed data are made available, the F-7 figures can be further honed and updated. The Brazil study also includes estimates of forestry emissions of other greenhouse gases aside from carbon dioxide in its analysis. Future studies for other countries also should aim to calculate quantities of all of GHGs generated by forest activities and their contribution to global climate change.

The next phase of this project will focus on identifying and analyzing response options for reducing emissions of carbon dioxide from forest-related sources. The information presented in this paper will provide the basis for detailed examinations of these policy issues. In addition, all of the researchers are carrying out economic evaluations of the various response options to determine their viability.

This study provides detailed information where previously only guesstimates were available. Nonetheless, this work was still hindered by the unavailability of needed information and the imprecision of existing data. In the future, more effort must be taken towards developing a better understanding of the deforestation process and the resultant carbon emissions. In particular, sounder estimates of the key parameters of the deforestation process must be developed as well as the extent of forested areas. Estimates of biomass density, for example, must be refined to more accurately reflect the composition of the forest. The new estimate of biomass density for Brazil used in this study (which is 40 percent higher than previous estimates) translated into a dramatically different estimate of forestry emissions from Brazil than those provided by past studies. Not only should this indicator be calculated with greater precision for other countries, but, in addition, the various other key indicators (e.g., soil carbon content, the nature of the decomposition process, etc.) must be approached in the same manner.

Carbon uptake plays a crucial role in a country's carbon flux. This work does a preliminary analysis of this significant phase in the carbon cycle, but recognizes the need for a more in-depth understanding of the sequestration process. In order to improve estimates of carbon uptake, two key areas must be further investigated: (1) uptake from trees outside the conventional forestry sector and (2) uptake from fallow forests. Typically, studies on forestry emissions have not focused on conducting national inventories, but instead have examined emissions from the forestry sector. As a result, trees located outside of forests (e.g., in agro-forestry, urban areas, etc.) have not been incorporated into past analyses. In fact, the above-listed non-forest trees may account for a substantial level of carbon uptake each year.

Quantifying these sequestration sources certainly will prove a challenge, because the types of inventories available at the national level for forest resources simply do not exist for agricultural activities, urban trees, etc. However, the role of trees outside the forest must be considered in order to develop a fuller picture of national carbon balances. Of equal importance is carbon sequestration from fallow forests. After deforestation occurs, secondary regrowth (and, thus, carbon uptake) takes place. This study estimates future uptake resulting from fallow forests as a result of deforestation activities in the base year. However, the preliminary estimates of inherited uptake do not include carbon uptake by fallow forests from past years' deforestation. The incorporation of uptake estimates from fallow forests from both past and present deforestation would lead to a substantial decline in the figures for annual carbon balance and net committed carbon provided here.

Calculating levels of future uptake requires data on how land deforested in the base year will be used over the long term. Because there is no way to predict the types of changes coming years will bring, this study made certain assumptions about future land-use patterns (e.g., what share of the deforested land will be converted to pasture, what share will become secondary forests, etc.). The Brazil study utilized Markov matrices to estimate the long-term land-use composition of the deforested area. In most of the other cases, however, guesstimates were made. Although projections of future trends will always prove somewhat elusive, much work can still be carried out to improve such forecasts. In particular, a better understanding is needed of the successionary process of land-use change and the evolutionary patterns that occur as lands shift from forests to areas of secondary regrowth, to pastures, etc. These patterns are affected by a wide range of internal factors, including socio-economic trends (such as population growth), political decisions (such as subsidies for cattle ranchers) and rural development strategies, as well as by powerful international forces, including trade policies and the continuing high demand for meat and wood products from industrialized countries.

A number of other factors that have yet to be fully understood play a role in determining future uptake. For example, this study projects uptake based on present climate conditions and current levels of biomass productivity. In fact, some recent studies have indicated that changes in the climate could lead to a higher carrying capacity of forest biomass, which in turn could result in greater carbon sequestration. This issue of carbon fertilization deserves further consideration.

Because the importance of carbon emissions was not widely recognized until recently, information on past rates of deforestation is rarely available for developing countries. Due to this absence of data, this study could not derive estimates of inherited emissions with the same level of accuracy as it could emissions resulting from base year activities. As more thorough national inventories of deforestation and emissions become available, consistent time series can be developed which will provide a far better overview of deforestation and emissions trends.

8.2. Overview and Conclusions

The in-depth case studies summarized in this paper provide a more detailed picture of carbon emissions from deforestation and logging in Brazil, China, India, Indonesia, Malaysia, Mexico and Thailand than was previously available. Together, the seven developing countries represented in this work generated 837 MtC from deforestation and logging in 1990. Excluding China (which has not been included in most past studies), committed emissions from the F-7 countries totaled 702 MtC, an estimate which lies 35 percent below Myers's (1989) estimate for 1989 (795 MtC) and 76 percent below WRI's (1990) estimate for 1987 (1724 MtC). If carbon uptake during the base year is considered, the F-7 total drops by 30 percent to 589 million tons of carbon. Whereas previous studies have tended to overlook emissions resulting from deforestation and logging in China, this study found that Chinese forestry activities have a small net positive impact on emissions. Perhaps the most notable finding: inherited and prompt annual uptake from tree-planting activities and vegetative growth in all of the F-7 countries totaled 374 MtC in the base year and committed uptake reached 367 MtC. A preliminary F-7 estimate of 1990 global emissions from forest sources -- based on the F-7 figures for these seven LDCs and Myers (1989) estimates for the rest of the world -- places worldwide committed emissions from deforestation and logging at 1.1-1.7 GtC/year.

This work attempts to break down the many forces contributing to deforestation in the F-7 countries and places them in a uniform framework to provide clear, simple and consistent profiles of each of the countries studied. As the individual country papers illustrate, the forces propelling deforestation in all of the F-7 countries differ widely. For example, in Brazil the deforestation process is primarily fueled by the provision of government subsidies to large-scale cattle ranchers settling the Amazon; the government views the subsidies as a means of attaining the national goal of further securing Brazil's rights to the Amazon territories. In contrast, deforestation in Thailand is largely a product of land conversions by small-scale farmers and forest resource use by the more than 7 million Thais inhabiting the country's forests. Population growth, as opposed to government aspirations, has the most notable impact on the forest sector in Thailand. These findings emphasize the need for unique policy measures tailored to meet the individual needs of each country.

This work highlights several issues of critical importance to discussions of global climate change. First, carbon uptake must be considered with estimates of committed emissions in order to derive an accurate portrait of the net quantity of emissions generated by a country in a given year. The contrast between estimates of committed emissions and the annual carbon balance (uptake is subtracted from emissions in the latter indicator) for India, China and Malaysia underlines this point. Second, developing sound estimates of emissions from the tropical countries requires detailed studies to be carried out at the country level. This study initiates this process by carrying out studies in the countries that generate the majority of all forest-related emissions. This work needs to be expanded to include other forested countries where substantial clearing is taking place.

The above examples of Brazil and Thailand illuminate another crucial point: the CO_2 problem must be addressed from a broader perspective than it is at present. The build up of CO_2 in the atmosphere is a global environmental problem. However, the particular developmental needs and priorities of each developing country must be integrated into the measures for remedying the CO_2 problem in order to develop appropriate and viable responses that meet global standards and further national aspirations. In this light, the types of strategies that are pursued should take advantage of the carbon-storing capacities of tropical forests, ensure a sustainable supply of forest products to the dependent populations and maintain the local and regional ecological functions of the forests.

APPENDIX

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References

Armentano, T.V. and C.W. Ralston. 1980. The Role of Temperate Zone Forests in the Global in the Global Carbon Cycle. *Canadian Journal of Forest Research* 10:153-160.

Brotoisworo, E. 1992. *Forests and Related CO_2 Emissions in Indonesia: A Preliminary Estimate of the Carbon Balance*. Review draft for the Tropical Forestry Research Network. Lawrence Berkeley Laboratory, Berkeley, CA. March.

Browder, J.O. 1988. *Public Policy and Deforestation in the Brazilian Amazon.* In: R. Repetto and M. Gillis, *Public Policies and the Misuse of Forest Resources*, Cambridge University Press, Cambridge, pp. 247-298.

Deying, Xu. 1990. *Greenhouse Gas Emissions and Forests in China.* Poster paper at the Second World Climate Conference. 31 Oct. - 6 Nov. 1990, Geneva, Switzerland.

Deying, Xu. 1992. *Forest-related CO_2 Emissions in China: Current Estimates and Long-Term Forecasts*. Review draft country study for the Tropical Forest Research Network. Lawrence Berkeley Laboratory, Berkeley, CA, March.

Fearnside, P.M. 1990a. *Greenhouse Gas Contributions from Deforestation in Brazilian Amazonia*. Paper presented at the Chapman Conference on Biomass Burning. 19-23 March 1990, Williamsburg, Virginia, USA.

Fearnside, P.M. 1990b. *Deforestation in Brazilian Amazonia as a Source of Greenhouse Gases.* Paper presented at the Regional Conference on Global Warming and Sustainable Development: Perspectives from Developing Countries. Universidade de São Paulo, 18-20 June 1990, São Paulo, Brazil.

Fearnside, P.M. 1992. *Greenhouse Gas Emissions from Deforestation in the Brazilian Amazon*. Review Draft for the Tropical Forestry Research Network. Lawrence Berkeley Laboratory, Berkeley, CA. April.

Food and Agricultural Organization (FAO), United Nations. 1988. *An Interim Report on the State of Forest Resources in the Developing Countries.* FAO, Rome, Italy.

Freitas, M. 1990. *Brazil's Reforestation Aspects*. Paper presented at the Conference "Tropical Response Options to Global Climate Change", Sao Paulo, Brazil, Jan. 9-11.

Hao, W.M., M.H. Liu and P.J. Crutzen. 1990. In J.G. Goldammer (ed). *Fire in the Tropical Biota*. Berlin: Springer-Verlag.

Houghton, J.T., G.J. Jenkins and J.J. Ephraums (eds). 1990. *Climate Change: The IPCC Scientific Assessment.* Cambridge: Cambridge University Press.

Houghton, R.A., R.D. Boone, J.R. Fruci, J.B. Hobbie, J.M. Melillo, C.A. Palm, B.J. Peterson, G.R. Shaver, G.M. Woodwell, B. Moore and D.L. Skole. 1987. The Flux of Carbon from Terrestrial Ecosystems to the Atmosphere Due to Changes in Land Use: Geographical Distribution of the Global Flux. *Tellus* 39B:122-139.

Houghton, R.A. 1991a. Releases of Carbon to the Atmosphere from Degradation of Forests in Tropical Asia. *Canadian Journal of Forest Research* 21:132-142.

Houghton, R.A. 1991b. Tropical Deforestation and Atmospheric Carbon Dioxide. *Climate Change* (in press).

Intergovernmental Panel on Climate Change (IPCC). 1990. *Emission Scenarios prepared by the Response Strategies Working Group of the IPCC.* Report of the Expert Group on Emission Scenarios. New York.

IPCC. 1992. *Section A: Greenhouse Gases.* Draft Report. New York.

Ismail, R., I. Ahmad and F. Fakhruddin. 1992. *Carbon Emissions from Forest Activities in Malaysia: Current Status and Long-Term Scenarios*. Lawrence Berkeley Laboratory, Berkeley, CA. March.

Johns, A.D. 1988. Economic Development and Wildlife Conservation in Brazilian Amazonia. *Ambio* 17:302-306.

Johnson, W.C. and D.M. Sharpe. 1983. The Ratio of Total to Merchantable Forest Biomass and the Application to the Global Carbon Budget. *Canadian Journal of Forest Research* 13:372-383.

Kaul, O.L. 1991. Forest Biomass Burning in India. *TERI Information Service on Global Warming*. New Delhi 2(2):2-17.

Keeling, C.D., B. Bacastow, A.F. Carter, M. Heimann, W.G. Mook, S.C. Piper, H. Roeloffzen and T.P. Whorf. 1989a. A Three-dimensional Model of Atmospheric CO_2 Transport Based on Observed Winds: 1. Analysis of Observational Data. In: D.H. Peterson (ed), *Geophysical Monograph: Aspects of Climate Variability in the Pacific and the Western Americas*. Washington, D.C.: AGU, pp.165-236.

Keeling, C.D., S.C. Piper and M. Heiman. 1989b. A Three-dimensional Model of Atmospheric CO_2 Transport Based on Observed Winds: 4. Mean Annual Gradients and Interannual Variations. In: D.H. Peterson (ed), *Geophysical Monograph: Aspects of Climate Variability in the Pacific and the Western Americas*. Washington, D.C.: AGU, pp.305-363.

Makundi, W.R., J.A. Sathaye and A. Ketoff. 1990. *CO-PATH: A Spreadsheet Model Associated with Tropical Forest Use.* LBL Report No. 35255. Lawrence Berkeley Laboratory, Berkeley, CA.

Masera, O., M. Ordóñez and R. Dirzo. 1992. *Carbon Emissions from Deforestation in Mexico: Current Situation and Long-Term Scenarios.* Review Draft for the Tropical Forestry Research Network. Lawrence Berkeley Laboratory, Berkeley, CA. May.

Molofsky, J., E.S. Menges, C.A.S. Hall, T.V. Armentana and K.A. Ault. 1984. The Effects of Land-use Alteration on Tropical Carbon Exchange. In: T.N. Veziraglu (ed), *The Biosphere: Problems and Solutions.* Amsterdam, Netherlands: E.S.P., pp.181-184.

Myers, N. 1980. *Conversion of Tropical Moist Forests.* Washington, D.C.: National Academy of Sciences.

Myers, N. 1989. *Deforestation Rates in Tropical Forests and their Climatic Implications.* London: Friends of the Earth.

Office of Technology Assessment (OTA), United States Congress. 1991. *Changing by Degrees: Steps to Reduce Greenhouse Gases.* OTA-O-482. Washington, D.C.: U.S. Government Printing Office.

Pearman, G.I. 1988. Greenhouse Gases: Evidence for Atmospheric Changes and Anthropogenic Causes. In: G.I. Pearman (ed), *Greenhouse: Planning for Climate Change.* Australia: CSIRO, pp.3-21.

Ravindranath, N.H., B.S. Somashekhar and M. Gadgil. 1992. *Carbon Flow in Indian Forests.* Review draft for the Tropical Research Forestry Network. Lawrence Berkeley Laboratory, Berkeley, CA. March.

Sathaye, J. and A. Ketoff. 1991. *CO_2 Emissions from Developing Countries: Better Understanding the Role of Energy in the Long Term.* Volume I: Summary. LBL-29507 Rev. Lawrence Berkeley Laboratory, Berkeley, CA.

Schneider, S.H. 1989. The Changing Climate. *Scientific American* 261:70-79.

Seiler, W. and P.J. Crutzen. 1980. Estimates of Gross and Net Fluxes of Carbon Between the Biosphere and the Atmosphere from Biomass Burning. *Climate Change* 2:207-247.

Sungsuwan-Patanavanich, S. and L. Atipunampai. 1992. *Carbon Emissions from Deforestation in Thailand: An Application of the CO-PATH Mode.* Lawrence Berkeley Laboratory, Berkeley, CA. March.

Thailand Development Research Institute (TDRI). 1990. *Energy and Environment: Choosing the Right Mix*. Proceedings of the 1990 TDRI Year-End Conference, Industrializing Thailand and its Impact on the Environment, held in Ambassador City Jomtien, Chon Buri, December 8-9, 1990.

White, F. 1983. *The Vegetation of Africa*. Paris: UNESCO.

World Resources Institute (WRI). 1990. *World Resources 1990-91*. New York: Oxford University Press.