United States
Environmental Protection
Agency

Office of Research and Development
Environmental Research Laboratory
Corvallis OR 97333

EPA 0/R-95/044
January 1

EPA

The Contribution of Forest Land Use To Total National Carbon Flux: Case Studies in the Former Soviet Union, United States, Mexico, and Brazil

The Contribution of Forest Land Use to Total National Carbon Flux: Case Studies in the Former Soviet Union, United States, Mexico and Brazil

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January 1995

EPA/600/R-95/044

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USA

Key Words

Carbon, Forest, Land use, Former Soviet Union, United States, Mexico, Brazil

Preferred Citation

Cairns, M.A., T.P. Kolchugina, D.P. Turner, and J.K. Winjum (Eds.). 1995. The contribution of forest land use to total national carbon flux: Case studies in the former Soviet Union, United States, Mexico and Brazil. EPA/600/R-95/044. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

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The information in this document has been funded wholly by the U.S. Environmental Protection Agency. It has been subjected to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Acknowledgments

The editors gratefully acknowledge all persons whose contributions led to the completion of this report. In particular, we thank the following individuals:

Writers and Technical Advisors:

J. Barker, ManTech Environmental Research Services Corp. (MERSC), contributed the discussion of modeling in Section VII. G. Baumgardner, Computer Services Corporation (CSC), contributed data base management for Section IV. M. Cairns, U.S. Environmental Protection Agency (EPA), was primary author of Sections I, II and VII. T. Kolchugina, Oregon State University (OSU), was primary author of Section III on the former Soviet Union and contributed to Sections II and VIII. J. Lee, U.S. Environmental Protection Agency (EPA), contributed policy perspective to Section VII. R. Riley, National Council for Air and Stream Improvement (NCASI), was the primary author of Section V on Mexico. P. Schroeder, ManTech Environmental Research Services Corp. (MERSC), contributed to Section VI. D. Turner, ManTech Environmental Research Services Corp. (MERSC), was the primary author of Section IV on the conterminous United States, contributed to Section II and VIII, and provided the comparison of national carbon fluxes in Section VII. T. Vinson, Oregon State University (OSU), contributed to Section III. J. Winjum, National Council for Air and Stream Improvement (NCASI), was the primary author of Section VI on Brazil, and Section VII and contributed to Sections II and VIII.

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M. Schuft, ManTech Environmental Research Services Corp. (MERSC)
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Terminology, Units and Acronyms

In this document:

- Phytomass refers to live plant material, both above- and belowground (i.e., live roots).
- Total ecosystem carbon (TEC) in is the sum of the carbon in Mg on a site which is contained in the phytomass, the dead organic matter (i.e., litter as well as the coarse woody debris), and the soil organic C.
- Pools and flux of biomass or carbon dioxide are expressed as carbon (C).
- Carbon flux values in the text, tables, and figures are designated with a plus sign (+) for C sequestration or uptake and a minus sign (-) for emissions from the biosphere.
- Units of measure are metric by The International System of Units (SI) or acceptable equivalents. Frequently used units in the report and equivalents are:

Pg (petagram)	= 10^{15} g
	= Gt (gigaton)
	= billion metric tons
Tg (teragram)	= 10^{12} g
	= Mt (megaton)
	= million metric tons
Mg (megagram)	= 10^{6} g
	= 10^{3} kg
	= one metric ton
ha (hectare)	= 10^{4} m^2
	= 10^{-2} km^2

Acronyms

CCAP:	Climate Change Action Plan (Clinton and Gore 1993)
CFC:	chloroflourocarbon
CH_4:	methane
CNIF:	Camara Nacional de la Industria Forestal, Mexico
CO_2:	carbon dioxide
CWD:	coarse woody debris
ERL-C:	Environmental Research Laboratory-Corvallis (U.S. Environmental Protection Agency)
FAO:	Food and Agriculture Organization of the United Nations
FCCC:	Framework Convention on Climate Change
FIA:	Forest Inventory and Analysis
FSU:	former Soviet Union
GCRP:	Global Change Research Program

GIS: geographic information system
GPP: gross primary productivity
GHG: greenhouse gases
GS: growing stock
IBDF: Instituto Brasileiro de Desenvolvimento Florestal, Brazil
IBGE: Instituto Brasileiro de Geografia e Estatistica, Brazil
INPE: Instituto Nacional de Pesquisas Espaciais, Brazil
IPCC: Intergovernmental Panel on Climate Change
N_2O: nitrous oxide
NAPh: net accumulation of phytomass
NACWD: net accumulation of coarse woody debris
NASOM: net accumulation of soil organic matter
NEP: net ecosystem productivity
NIW: net annual accumulation of stem wood
NPP: net primary productivity
NRI: National Resources Inventory
R_A: respiration of autotropic organisms (or alitotrophic respiration)
R_H: heterotrohic respiration
SARH: Secretaria de Agricultura y Recursos Hidraulicos, Mexico
SCS: Soil Conservation Service, U.S. Department of Agriculture
SOM: soil organic matter
TEC: Total ecosystem carbon
UNAM: Universidad Nacional Autonoma de Mexico
UNCED: United Nations Conference on Environment and Development
UNESCO: United Nations Educational, Scientific, and Cultural Organization
USDA: U.S. Department of Agriculture
WRI: World Resources Institute

Executive Summary

Various human activities are causing an increase in emissions to the atmosphere of carbon dioxide CO_2 and other greenhouse gases, for example CH_4, N_2O, and CFCs. The annual increase in atmospheric CO_2 concentration approximates 1.5 ppm (Houghton et al. 1990). Although the dynamics and feedbacks are poorly understood (Houghton et al. 1992; Sundquist 1993), scientific consensus maintains that the increased atmospheric concentrations will cause an increase in global mean temperature and alterations in related components of the Earth's biogeochemical cycles. Researchers predict the global mean temperature will rise between 0.2 and 0.5°C per decade (Houghton et al. 1990), or from 1.5 to 4.5°C in the first half of the 21st century (Schlessinger and Mitchell 1985; Hansen et al. 1988; Mitchell 1989; Manabe et al. 1991).

Fossil fuel burning, the single largest source of CO_2, is estimated to produce 5.4 ± 0.5 PgC/yr, with an additional net contribution of 0.9 ± 0.4 PgC per year from deforestation, vegetation growth, and other land-use changes (Dixon et al. 1994). Oceans absorb 2.0 ± 0.8 PgC/yr and 3.2 ± 0.1 PgC/yr remains in the atmosphere, leaving unaccounted approximately 1.1 ± 1.0 Pg/yr (Dixon et al. 1994). It is theorized that the world's forests are the "missing C sink" (Tans et al. 1990; Lugo and Brown 1992; Taylor and Lloyd 1992).

The United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in June 1992, agreed to a Framework Convention on Climate Change (FCCC). The objective of the FCCC is to

> "...achieve...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate

system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner." (UNCED 1992)

The Convention, which went into force in March, 1994, requires that each nation prepare an inventory of greenhouse gases.

This project assessed forest ecosystem land-use and land-cover change and their impacts on C dynamics. At the national level, the former Soviet Union (FSU), the United States (48 conterminous states), Mexico and Brazil were examined in detail to estimate C pools and flux rates. Carbon storage and emissions of the four nations were compared to identify trends and patterns in relation to biogeography and level of economic activity. The prominent role of global forests in the total terrestrial C pool and the large annual quantities of C moving through global biogeochemical cycles are reported. The report describes approaches to estimating C dynamics at the national scale.

The biogenic C cycle consists of a combination of pools and fluxes. Pools are C stores in soil and vegetation, including living vegetation (i.e., phytomass), coarse woody debris (CWD, aboveground and belowground), soil, and litter. Processes associated with formation of new organic matter in soil and vegetation (i.e., humification and NPP) represent C influxes. Efflux is associated with C emissions resulting from plant respiration and decomposition of organic matter. Combustion of organic matter associated with wildfires, slash burning, and peat utilization represents the other major biogenic C efflux.

Forest ecosystem land-use change is estimated to contribute annual emissions totaling from 0.5 to 1.3 PgC (Dixon et al. 1994). The four case study countries in this report accounted for approximately 46% of the world's total forest area (Makundi

et al. 1992; FAO 1993; Kolchugina and Vinson 1993a; Turner et al. 1993a). Regrowth of formerly degraded or disturbed forests may largely balance the flux associated with land-use change (Kauppi et al. 1992). In addition, the assumption that forests that have not been cleared within the past 100 years or so are in C equilibrium (Houghton et al. 1983) is not currently supported (Lugo and Brown 1992).

This assessment of net C exchange between the atmosphere and the biosphere employed examination of biological processes in forest ecosystems, harvest of trees for wood and paper products, and direct C emission from fires. Critical processes considered include those associated with the forest land base, forest products and landfills, and anthropogenic emissions. Quantified land-base processes were changes in the intensity and extent of forest use, such as growth, mortality, decomposition, harvest and fire. Outside the forests, agricultural practices, peat accumulation, cement production, landfills, and fossil fuel production and use were also considered.

Methods of modeling biogenic C dynamics varied in this study because of inherent differences among boreal, temperate and tropical biogeographic zones. Examples of such differences include peat accumulation (boreal), increasingly intensified forest management (temperate), and paucity of forest inventory information (tropical). Assessments varied among countries, because of both quality and quantity of data available in the following order: U.S. > FSU > Brazil > Mexico.

Land area of the FSU, U.S., Mexico, and Brazil total 3.92×10^9 ha, about 30% of the Earth's total land area. These countries contained 35% of the world's closed forests, 26% of the woodlands, and 38% of the total croplands. Carbon densities in these common vegetation types ranged from 184 to 271 Mg/ha in closed

forests, from 88 to 241 Mg/ha in woodlands, and from 80 to 156 Mg/ha in croplands.

The terrestrial ecosystems of the four countries contained approximately 866 PgC, or about 44-52% of the world's total, with the FSU alone having one-third of the global total. Of this amount, forest C pools of the four countries were as follows (in PgC): 138 (FSU), 109 (Brazil), 37 (U.S.), and 14 (Mexico). Average forest phytomass C densities decreased from south to north as follows (in MgC/ha): 152 (Brazil), 64 (Mexico), 63 (U.S.), and 70 (FSU). While densities were much lower in woodlands and croplands, the increasing north-to-south trends followed for phytomass C densities. Average litter and CWD C densities of forest/woodlands ranged from highs of 30 Mg/ha in U.S. forests and 16 Mg/ha in FSU woodlands to lows of 7 Mg/ha in Mexican forests and 2 Mg/ha in both Mexican and Brazilian woodlands. Average soil C densities in all three vegetation types generally increased from south to north, ranging from 123 Mg/ha in FSU woodlands to 60 Mg/ha in Brazilian woodlands.

For the C flux comparison, land-base C flux was separated from the set of all C flux terms. The land-base flux was divided into a net biological term and a land-use/land-cover change term. The net biological flux refers to the expected change in C storage on the land base if no further anthropogenic impacts were imposed. Thus it included "inherited" emissions from previous disturbances. The components of the net biological flux were the net changes in the pools of phytomass, CWD, and soil organic matter. The net change in the phytomass pool—a balance of woody phytomass growth and mortality—was positive in all four countries and relatively high in the FSU, the U.S. and Brazil because large areas of young forest stands promoted C accumulation. The total net biological flux (in Tg/yr) was positive in the FSU (631) and the U.S. (332), but negative in Mexico (37) and Brazil (16).

Besides net biological flux, the other main land-base flux was associated with anthropogenic land uses. Components included (1) removal of wood during commercial harvest, (2) direct emissions from burning (deforestation in the tropics and timber harvest slash burns in temperate and boreal countries), (3) soil C emissions from tillage of agricultural soils, and (4) peat combustion. Total land-use flux was negative (i.e., were emissions) in all four countries (in TgC/yr): FSU (-342), U.S. (-243), Mexico (-35), and Brazil (-235).

The total net effect of the biological and anthropogenic factors on the land base was a C sink in the FSU and the U.S. and a C source in both Brazil and Mexico.

In the complete country level C budgets, four additional flux components were included. The accumulation of C in forest products still in use ranged from 36 and 33 Tg/yr in the U.S. and FSU, respectively, to 3 and 1 Tg/yr in Brazil and Mexico, respectively. Accumulation in landfills was greatest in the U.S. and FSU (10 TgC/yr), but this was a relatively small flux term in all four budgets. Emissions from energy production and use was the dominant term in the U.S. (1296 TgC/yr), FSU (1020 TgC/yr), and Mexico (74 TgC/yr) budgets, whereas in Brazil the net land-base flux (-251 TgC/yr) was dominant.

In all cases, C sources exceeded sinks, i.e. all countries were net emitters of C. The U.S. is the largest emitter because of its high per capita industrial emissions and large population. The FSU had a similar distribution of sources and sinks and, like the U.S., was a large net emitter. The estimated land-base sink in the FSU accounted for a much larger proportion (41%) of the total C source than was the case in the U.S. (8%). Brazil was notable because the land-base source was larger than the industrial source. In Mexico, industrial emissions were of about the same magnitude as the land-base source. The summed net

emissions from these four countries (2347 TgC/yr) represented about 36% of the estimated global net CO_2-C emission.

To improve assessments of C flux due to land-use and land-cover change, data are required for (1) classifying land cover and its relative change over time due to land-use change, (2) quantifying C mass per unit area--C densities--of the various land-cover classes, and (3) quantifying C flux per unit area within the specific land-cover types. Research needs specific to the three biogeographic zones include C accumulation in CWD/soils/peat and frequency/extent/intensity of fires (boreal zone); improved forest inventories and soil/CWD C dynamics following harvest (temperate zone); and secondary forest regrowth, possible mature forest C accretion vs. equilibrium, and lotic C export (tropical zone).

I. Introduction

A. Global Change and the International Response

Human activities are causing an increase in emissions to the atmosphere of CO_2 and other greenhouse gases, for example CH_4, N_2O, and CFCs. The annual increase in atmospheric CO_2 concentration approximates 1.5 ppm (Houghton et al. 1990). Scientific consensus maintains that the increased atmospheric concentrations may cause an increase in global mean temperature and alterations in related components of the Earth's biogeochemical cycles. The dynamics and feedbacks are, however, poorly understood (Houghton et al. 1992; Sundquist 1993). Current predictions indicate that the global mean temperature will rise between 0.2 and 0.5°C per decade (Houghton et al. 1990), or 1.5 to 4.5°C in the first half of the 21st century (Schlessinger and Mitchell 1985; Hansen et al. 1988; Mitchell 1989; Manabe et al. 1991; Houghton et al. 1992).

Fossil fuel burning, the single largest source of CO_2, is estimated to produce 5.4 ± 0.5 Pg carbon (C) per year, with an additional net contribution of 0.9 ± 0.4 PgC/yr from deforestation, vegetation growth, and other land-use changes (Dixon et al. 1994). Oceans absorb 2.0 ± 0.8 PgC/yr and 3.2 ± 0.1 PgC/yr remains in the atmosphere, leaving unaccounted approximately 1.1 ± 1.0 PgC/yr (Dixon et al. 1994). It is theorized that the world's forests are repositories of this "missing C sink" (Tans et al. 1990; Taylor and Lloyd 1992).

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization and the United Nations Environment Program. This panel has sought to draw together scientific research on global warming, assess impacts on human and natural systems, and recommend appropriate

actions to mitigate or adapt to the impacts. The IPCC began discussions and analyses that led to an international convention on climate change in 1992 (Parson et al. 1992).

B. Framework Convention on Climate Change Mandates National Greenhouse Gas Emissions Inventories

The United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in June 1992, drafted a Framework Convention on Climate Change (UNFCCC), which was signed by 161 nations. It was ratified by the minimum 50 countries and went into force on March 21, 1994. As of July 13, 80 countries had ratified and are now legally bound by the terms of the UNFCCC. Developed countries were to submit national action plans for reducing GHG emissions by September 21, 1994. Developing countries have three additional years. The first session of the conference of the signatories opens on March 28, 1995 in Berlin. The objective of the UNFCCC is to

> "achieve...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner." (UNCED 1992)

The Convention requires each nation to prepare an inventory of anthropogenic greenhouse gases. Such inventories will enable nations to (1) set priorities for controlling emissions from different sources and economic sectors and (2) verify progress toward achieving emission reduction targets.

The United States recently published the national response strategy to reduce emissions to 1990 levels by 2000 (Clinton and Gore 1993). The U.S. Climate Change Action Plan (CCAP) commits the U.S. to a target of 1,500 Tg CO_2-C or equivalents, requiring a net annual reduction in projected emissions of 106 TgC by 2000. Implementation of the CCAP calls for establishment of public-private partnerships with key industries to reduce greenhouse gas emissions across many sectors of the U.S. economy. The CCAP lists 50 separate actions selected for effectiveness, rapid implementation, and low cost. Included in the plan are three actions relating specifically to the forest sector, designed to provide a net reduction of 9.5 TgC annually or approximately 9% of the total specified emission reductions. The forest sector actions are

- Accelerated source reduction, pollution prevention, and recycling
- Assistance for improved timber management on nonindustrial private forest lands
- Accelerated tree planting on nonindustrial private forest lands

C. U.S. Government, Environmental Protection Agency and Environmental Research Laboratory-Corvallis Roles

The U.S. government, through its interagency Committee of the Environment and Natural Resources of the National Science and Technology Council, developed the U.S. Global Change Research Program (USGCRP). The program, designated as a National Research Program, aims to provide a sustained, long-term effort for global change research within the federal government. The USGCRP seeks to produce a predictive understanding of the earth system and its biogeochemical cycles to support national and international

policy decisions across a range of environmental issues. Four working groups of the USGCRP address these broad activities:

- Observations and data management
- Process research
- Integrated modeling and prediction
- Assessments

Research at the U.S. EPA Environmental Research Laboratory - Corvallis (ERL-C) is conducted in each activity group, within the EPA's GCRP. Process research at ERL-C is described in the Global Processes and Effects Program (1993); integrated modeling and prediction research is described in U.S. EPA (1993). The current report was an assessment-oriented research product. Other recent ERL-C GCRP assessment projects are described in Dixon et al. (1991) and Turner et al. (1993a).

D. Purpose, Scope and Organization

This study assessed forest ecosystem land-use change and its impact on C dynamics. At the national level, the largely boreal zone FSU, the temperate zone U.S. (conterminous states), and the tropical zone nations of Mexico and Brazil were examined in detail to estimate C pools and flux. Carbon storage and emissions of these four countries were compared to identify trends and patterns in relation to biogeography and level of economic activity. The report discusses the prominent role of global forests in the total terrestrial C pool and the large annual quantities of C moving through global biogeochemical cycles.

The report also describes approaches to estimate C dynamics at the national scale by quantifying processes including changes in the intensity and extent of forest use, including growth, mortality, decomposition, harvest and fire. Two additional processes,

while not primary foci of this report—the fate of harvested forest products and anthropogenic C emissions from other sources—are discussed in the context of national and global C flux. A review of C budget models puts the modeling approach of this report in context.

For each country, background information supplies the context for current C pools of the various land-cover/land-use types, current overall C flux, including fossil fuel emissions, and possible forest management options for conserving terrestrial C and sequestering atmospheric C.

II. Background

The C cycle consists of a combination of pools and fluxes. The pools are C stored in soil and vegetation, including living vegetation (i.e., phytomass), coarse woody debris (CWD, aboveground and belowground), soil, and litter (Kolchugina and Vinson 1991; Vinson and Kolchugina 1993). The term litter includes fine woody debris and leaves that are not completely decomposed. The processes associated with formation of new organic matter in soil and vegetation (i.e. humification and NPP) represent C influxes. Efflux is associated with C emissions resulting from plant respiration and decomposition of organic matter. The NPP equals the difference between GPP and R_A. The R_A amounts to 44% to 52% (48% on average) (Kobak 1988) of GPP. NEP is NPP minus heterotrophic respiration; it can be measured as the net increase or decrease of C in the soil, phytomass, CWD, and litter after C is expended for autotrophic and heterotrophic respiration.

The NEP may be positive, zero or negative at the beginning of secondary succession depending on the combination of NPP soil respiration and previous land use. The NEP increases with time reaching a maximum at some intermediate age, depending on forest type, e.g., 20 to 80 years for Russian forests (Vorobyov 1986; Kolchugina and Vinson 1993d). In a climax ecosystem, it is hypothesized that the rate of autotrophic and heterotrophic respiration is high, and NEP may approach zero.

A. The Importance of Forests in the Global Carbon Cycle

Land-use change currently contributes an amount of C equivalent to 17% of the net emissions of fossil fuel burning (Dixon et al. 1994). This proportion represents a decrease from 30% in the 1980s (Houghton et al. 1992; Sarmiento and Sundquist 1992).

Because their total ecosystem carbon (TEC) is large, the world's forests are the primary ecosystems whose alteration contributes to these land-use based C emissions (Solomon et al. 1993).

The main pools of the global carbon cycle are oceans, containing approximately 38,000 PgC, followed by fossil fuel deposits (4,000 PgC), litter and soil organic matter (1,100-1,600 PgC), and the atmosphere (750 PgC) (Post et al. 1990; Smith et al. 1993; Sundquist 1993). Global vegetation contains 420-830 PgC, the range in values indicating the uncertainty in ecosystem classification, as well as area and carbon density of each vegetation class (Post et al. 1990). However, plants exert a large influence on C dynamics due to the processes of photosynthesis, respiration and decomposition (Simpson and Botkin 1992; Woodwell 1992). It is estimated that the entire atmospheric CO_2 content cycles through the terrestrial biosphere every seven years, with approximately 70% of that C exchange passing through the Earth's forest ecosystems (Waring and Schlesinger 1985).

Forests occupy approximately 4.1×10^9 ha, or 31% of the Earth's surface (Allan and Lanly 1991; WRI 1992). Of this total, the boreal biome currently contains 33%, temperate regions 25%, and the tropics 42% of the world's forest area (Dixon et al. 1994). The nations of the FSU, U.S., Mexico and Brazil account for approximately 46% of the total forest area (Makundi et al. 1992; FAO 1993; Kolchugina and Vinson 1993a; Turner et al. 1993a). Forests of the world store 40% of the total belowground and nearly 80% of the total aboveground terrestrial C (Olson et al. 1983; Schlesinger 1984; Zinke et al. 1984; Waring and Schlesinger 1985; Allan and Lanly 1991; Dixon and Turner 1991; WRI 1992; Schindler and Bayley 1993). Forests currently contain 75% of the world's living C (Houghton et al. 1993).

Employing a 1980 base year, forest ecosystem land-use change has been estimated to contribute annual emissions totaling from 0.4

to 2.5 PgC (Houghton et al. 1983, 1987; Detwiler and Hall 1988; Houghton and Skole 1990; Flint and Richards 1994). A more recent estimate has reduced this uncertainty to a global net flux of 0.5 to 1.3 PgC (Dixon et al. 1994). Regrowth of formerly degraded or disturbed forests may largely balance the flux associated with land-use change (Kauppi et al. 1992). In addition, the assumption that forests that have not been cleared within the past century are in C equilibrium (Houghton et al. 1983) is not currently supported (Lugo and Brown 1992).

B. Approach to Estimating Carbon Flux at the National Scale

An assessment of net C exchange between the atmosphere and the biosphere must involve examination of biological processes in forest ecosystems, conversion of forests to alternate land covers, harvest of trees for wood and paper products, and direct C emission from fires. Outside the forests, agricultural practices (particularly tillage intensity and emissions from rice and livestock production), peat accumulation (in boreal zones), cement production, landfills, and fossil fuel production and use must also be considered. Although this report focused on land-use, other greenhouse gas sources and sinks are also discussed.

1. Critical Processes

Flux is the rate of movement of C from one pool to another. The principal forest vegetation C pools include both live and dead matter. Live aboveground pools include stemwood, bark, branches, foliage, shrubs and herbs; the primary live belowground pool is root phytomass. The aboveground dead C pools are standing and fallen logs, and litter; the primary dead belowground C pools are soil and dead roots. Other C pools (e.g., animals) exist although they are usually ignored in C budgets because they are a

relatively small portion of the ecosystem totals. Carbon pools are frequently aggregated due to the difficulty of measuring individual pools or the small contribution of particular pools to the total ecosystem C content.

Biological processes that result in changes in forest C pools include primary production, litterfall, mortality, grazing, and autotrophic (R_A) and heterotrophic (R_H) respiration. Ideally C movement between all pools would be measured (Table II.1). Because some processes are relatively unimportant or very difficult to measure, net changes are usually quantified rather than the processes themselves. The flux components typically quantified are net tree growth, net change in litter and understory, net change in dead vegetation components (input from mortality and output from decomposition), and net change in soil C (including peat and agricultural tillage) over a specified time period (e.g., one year). Net flux in an ecosystem can be represented as

NEP = NPP - (heterotrophic respiration - loss from leaching),

where

NPP = (change in live above- and belowground phytomass) + (litterfall + wood mortality + grazing + root mortality).

a. Forest Land Base

Natural and human-induced mortality of trees causes succession, which influences C flux at various stages. Knowledge of the forest age structure is valuable in assessing C flux in forested nations although age structure is not readily determined in the tropics. NEP depends upon age structure of forest ecosystems, approaching zero near the start of successional processes, gradually increasing and reaching its maximum near the mid-point of succession, a time dependent upon the particular biogeographic zone. In most climax ecosystems, NEP again approaches zero

Table II.1. Carbon Fluxes and Assumed Pools*

Flux	Donor pool	Receptor pool
Litterfall		
Conifer needles	Tree foliage	Litter
Hardwood leaves	Tree and shrub foliage	Litter
Woody	Tree wood parts, except stemwood	Litter
Reprod. parts	no pool	Litter
Other	no pool (epiphytes, grass, insects and unidentifiable)	Litter
Herb turnover	Herb	Litter
Tree mortality	Tree woody parts Coarse roots	Standing dead
Grazing	Foliage from all vegetation strata	Atmosphere
Autotrophic respiration		
Aboveground	Aboveground tree components	Atmosphere
Belowground	Coarse & fine roots	Atmosphere
Heterotrophic respiration		
O horizon	O horizon	Atmosphere
Standing & fallen logs	Standing & fallen logs	Atmosphere
Mineral soil	Mineral soil	Atmosphere
Gross primary production		
Aboveground	Atmosphere	Aboveground vegetation
Belowground	Atmosphere	Belowground vegetation
Net primary production		
Aboveground	Atmosphere	Aboveground vegetation
Belowground	Atmosphere	Belowground vegetation
Leaching loss	no pool	Out of ecosystem
Net ecosystem production		
Aboveground	Atmosphere	Aboveground vegetation
Belowground	Atmosphere	Belowground vegetation

*Modified from Grier and Logan (1977).

because of the high rate of autotrophic and heterotrophic respiration.

Carbon is removed from forest ecosystems when vegetation is removed for wood and paper products, for use as fuelwood, for charcoal, and for non-wood forest products (FAO 1993). National imports and exports of both long-lived wood products (e.g., structural lumber and furniture) and short-lived products (e.g., paper and paper board) are economic processes involving C from forests. These processes need to be factored into national C budgets. Current roundwood production--including industrial roundwood, fuelwood and charcoal--in the four nations that are the focus of this report equals 1.139×10^9 m^3, or 33% of the world's total. Fuelwood and charcoal consumption in these countries totals 0.373×10^9 m^3, or 20% of the world's total (FAO 1993). It should be noted, however, that international negotiations have yet to reach agreement on credit and responsibility for C emissions due to import and export of forest products.

Carbon is lost to the atmosphere when phytomass is removed from forests as products and from harvest-associated processes, including slash burning of understory as well as increased formation of litter and coarse woody debris that subsequently undergo oxidation to CO_2. In addition to current direct impacts on C flux in forest systems, harvest may cause indirect, future effects on primary production and heterotrophic respiration that impact C flux.

Direct CO_2 emissions occur during wildfire, forest management practices (e.g., slash burning and prescribed fire suppression burns), agricultural burning (e.g., crop residues and grasslands), and shifting cultivation burning. The largest source of C emissions from the Earth's forest land base, however, is due to conversion of forest to pasture or croplands, when trees are cleared and burned to create bare land or grasslands. These

sources have proven to be difficult to isolate and quantify (Levine 1991).

b. Products and Landfills

Wood and paper products have particular half-lives. Structural and furniture wood may have turnover times of many decades, whereas paper products have lives ranging from weeks or months to a few years. In order to assess flux from product decay in any base year, products from trees harvested both currently and in the past should be counted. A detailed C accounting is typically used to quantify fluxes from all wood products and landfills.

Landfills are repositories for forest products and act as both sinks and sources of greenhouse gases (Subak et al. 1993). Wood and paper products deposited in landfills must be accounted. Models continue to be developed (e.g., Row and Phelps 1990) to account for transport of forest products C to landfills and for the subsequent release of C from landfills. These models must account for both current release of C from past wood product landfilling and future C release from current product landfilling.

c. Anthropogenic Emissions

Carbon emissions from anthropogenic sources, principally fossil fuel production and combustion and cement manufacture, must be parts of any national C budget. Because these statistics are more regularly maintained, the accounting is less difficult than for processes associated with land-use change. In 1988, the four countries of this report emitted 2.440 PgC, or 44% of the world's total emissions from the energy sector. During the same year, the four nations emitted 35.08 MgC, or 23% of the world's total C from cement production (Subak et al. 1993).

Another form of C emissions, CH_4 results from energy production and use, landfills, phytomass burning, decomposition following timber harvest, livestock production and rice cultivation. Carbon monoxide, released during phytomass burning and fossil fuel production and use, is likewise a C source, exerting its influence by being oxidized to CO_2 in the atmosphere (Houghton et al. 1992). Other greenhouse gases include N_2O, produced by biotic processes and accelerated by fertilizer use and the numerous halocarbons used in various industrial and household applications.

2. Special Issues for Carbon Budgets in the Three Biogeographic Zones

Certain characteristics typify each biogeographic zone and influence C budgets. Temperature, climate, topography, soils and decomposition rates are among the characteristics. The zones represented in this study were boreal, temperate and tropical.

a. Boreal Zone

The FSU contains boreal ecosystems characterized by a significant accumulation of CWD and litter due to relatively cold temperatures and low decomposition rates compared to temperate and tropical ecosystems. The CWD and litter are thus important components of the C budget of boreal forests. The CWD must, therefore, be explicitly accounted for in the NEP estimates.

Peatlands, which are wetlands where peat is accumulating, store significant amounts of carbon. The organic soil carbon content of boreal peatlands may reach 2,000 MgC/ha (Bohn 1982). Wetlands are a source of CH_4 released to the atmosphere. Although the atmospheric concentration of CH_4 is much lower than the

concentration of CO_2, CH_4 is 20 times more effective (per molecule) than CO_2 as a greenhouse gas (Blake and Rowland 1988).

Development of boreal forests is influenced by disturbances, such as fires, logging and insect attacks. Disturbances may partly or completely kill the vegetative component of the ecosystem. Climatic constraints e.g., low temperatures and the presence of permafrost, do not allow rapid regeneration. Consequently, definite age structure characterizes boreal forests; a significant presence of young stands is a result of the influence of disturbances and slow regeneration. Knowledge of the forest age structure is important in the assessment of the C flux within forest ecosystem regions.

b. Temperate Zone

In the absence of human disturbance, deciduous forests of the temperate zone tend to be in C equilibrium at the stand level; gaps created by large tree falls maintain a shifting mosaic steady state (Bormann and Likens 1979; Runkle 1985). Patches dominated by young trees where carbon is accumulating alternate with patches where woody debris decomposition creates a carbon source. Temperate zone coniferous forests may likewise be in C equilibrium although a somewhat larger spatial context must be considered; large disturbance events such as catastrophic fires tend to create a shifting mosaic of stands at different ages (Franklin and Hemstrom 1981). In recent history, the natural disturbance regimes have been augmented by disturbances associated with human activities. At its extreme, this human activity has meant the loss of large areas of forests due to land-use change or degradation with an associated large release of C. In the conterminous U.S., for example, current forest cover is about 55% of potential forest cover (Turner et al. 1993b).

Anthropogenic influences have also meant an altered species composition and age class distribution.

Rates of deforestation in developed temperate zone countries have tended to decrease in recent decades (e.g., Alig et al. 1990) and in some cases significant reforestation has occurred (Kauppi et al. 1992). At the same time, the age-class distribution has been shifted towards relatively young stands with high rates of C uptake. Thus, although harvest rates have tended to increase over time, the forest land-base in many cases is a C sink (Sedjo 1992). The forests have, in general, come under intensified management. Several aspects of intensified forest management are essential to consider in a C budget.

First is the C transfer at the time of harvest. Only about half of the C in trees that are harvested is removed from the land-base (Harmon et al. 1990). The remaining C is either quickly returned to the atmosphere via slash burns or slowly returned via decomposition of woody debris.

Second, the disposition of the C which has been converted to forest products is important. Estimates of approximately 40% have been used for the proportion of forest products which go into long-term storage (Harmon et al. 1990; Birdsey et al. 1993). In principle, a C budget is needed which accounts for historical trends in harvest levels, the allocation of the harvest among product types, and product turnover times.

Third, a long-term effect of extensive harvesting followed by reforestation is to increase national-level tree growth. Rates of tree growth in late stand development tend to fall because of various physiological and nutrient cycling constraints (Sprugel 1985; Ryan and Waring 1992), so a shift to a younger age class distribution will generally induce greater growth. Note, however, that national carbon pools may be decreasing even as net

annual growth is increasing. A younger age-class distribution tends to contain less tree C density than an older age-class distribution in the same area. The input of carbon to the woody debris pool via natural mortality also tends to decrease as the age class distribution is shifted downward. In the absence of management intervention to promote woody debris formation, the effect of the mortality decrease may be a general decrease in the pool of woody debris.

In order to account for these various considerations associated with a harvest-dominated forest land base, the combination of an inventory and a set of yield tables and associated stand level C budgets is desirable. Although the degree to which woody debris and soil C are treated varies, this general approach has been applied in the U.S. (Plantinga and Birdsey 1993; Turner et al. 1994a), Canada (Kurz et al. 1992), and FSU (Kolchugina and Vinson 1993b).

A related approach to estimating forest C flux retrospectively employs inventory data from repeated forest surveys, i.e. the difference in the inventory across two points in time provides the basis for a change in C storage and hence a C flux. This approach has only been employed to estimate changes in tree C storage (Birdsey 1992; Kauppi et al. 1992); changes in forest floor, understory, woody debris and soil have not been treated. Other problems with the approach include the difficulty and cost of performing a complete resurvey of the inventory on a regular basis as well as possible differences in inventory approaches at different points in time.

c. Tropical Zone

For 1990, FAO (1993) reports that the tropical forest cover in the world totaled 1,756 X 10^6 ha. This forest area is about 37%

of all land in the tropics and is close to 45% of the world's forest cover. Tropical forests are located around the world roughly between latitudes 23°30'N and 23°30'S and are distributed among three broad regions (X 10^6 ha): Africa with 528; Asia & Pacific with 311; and Latin America & Caribbean with 918 (FAO 1993).

Tropical forests are contained, for the most part, in 90 nations which have been classified within the group of 140 nations in the world with "low" levels of income per capita, i.e., the "developing" or "in-transition" nations (Keating 1993). The 90 nations contain over 4 billion people (FAO 1993) or approximately 75% of the world's total population (Sitarz 1993). About 25% of the people have incomes equivalent to less than U.S.$1/day (Keating 1993). This context affects C flux determinations for tropical nations in two important ways.

First, most developing nations do not have accurate data on the C inventory, phytomass growth, or land-use changes (e.g., deforestation) in their forested areas. Pressing economic, social, and political issues have generally precluded intensive surveys of national forest resources. The 1990 assessment by FAO of the forest resources of the tropics (FAO 1993) is the most comprehensive yet produced. For the first time, FAO used GIS and remote sensing technology in such an undertaking. Despite this more technical effort, the 1990 inventory is still an estimate based on multi-date, sub-national inventory data and models. Increasing the precision in calculating the C flux for tropical nations, therefore, is limited until forest inventories become more widespread and accurate.

Second, in an attempt to improve their national economies and the conditions of their people, developing nations through history have been prone to rapid and unplanned exploitation of natural resources. This often results in increased rates of land-use

change. In recent years for forested nations of the tropics, development has led to high levels of deforestation to provide land for agricultural crops, pasturelands, dams, roads, settlements, or harvest of tropical hardwood trees. FAO (1993) estimates that the average annual deforestation rate in the tropics during the last decade was 15.4 X 10^6 ha. This deforestation rate is significant because, on a per ha basis, phytomass density levels for moist tropical forests are in the high category among the world's terrestrial ecosystems. Levels often approach 200 MgC/ha (Brown and Lugo 1982; Waring and Schlesinger 1985; Fearnside 1992). Thus, within individual tropical nations, land-use changes like deforestation may be the dominant source of emissions of C to the atmosphere. For example, in 1990, emissions from 1.3 X 10^6 ha of deforestation in Brazil were estimated to range from 69 to 97 TgC (Schroeder and Winjum 1995a and 1995b). Emissions from this one source were the largest for that nation and thus were about three times the 50 TgC from burning fossil fuels estimated for 1990.

Two other processes potentially important to C flux determinations for tropical forests bear mention: possible C uptake by so-called "mature" forest and the extent and growth rate of secondary forests. At present, there is not sufficient data available to confidently estimate the size of either phenomenon, but their possible significance warrants a brief description.

Despite deforestation, the tropical zone still has 1756 X 10^6 ha of mature forest cover (FAO 1993). Ecologists have often assumed that so-called "undisturbed" tropical forests not undergoing land-use changes are in C equilibrium, meaning a steady state without net C gains or losses. There may be, however, reason to question the steady state assumption. Lugo and Brown (1992) argue that the phytomass and phytomass accumulation rates of tropical forests change over time due to past disturbances by people and natural catastrophes. Citing plot level field data

from Venezuela and Puerto Rico, they show mature forests accumulating phytomass C at rates of 1-2 MgC/ha/yr. Data do not exist to quantify such increases worldwide, but Lugo and Brown (1992) surmise that if the mature tropical forests of the world in 1980 averaged as little as 0.25 MgC/ha/yr in net uptake by photosynthesis, they would remove annually about 1 PgC from the atmosphere (see Section VI.D.6).

Secondary forests regenerating on many of the recently deforested lands in the tropical zone now appear to sequester significant amounts of C. In Brazil, a large C flux in secondary forests results from the combination of phytomass growth and C accumulation in litter-CWD and soil. The current estimate is 260 TgC/yr based on 5 MgC/ha/yr accumulating in phytomass, litter and CWD, and soil (an average across all age classes) on 52 X 10^6 ha (Schroeder and Winjum 1995b). Generally however, knowledge is limited about the tropical zone on the extent and phytomass productivity of secondary forests (Brown and Lugo 1990). Uptake of C in total for these forests is likely a significant flux whose determination awaits better data (see Section VI.D.3).

3. River Transport of Carbon

Rivers contain C, which originates via runoff from terrestrial ecosystems, and transport it to the oceans. Globally, about 55% of this riverine C was recently in the atmosphere and fixed by photosynthesis; the remaining 45% is from weathering of rocks (Meybeck 1993). The global estimate of the C fixed from the atmosphere and transported by rivers is 540 TgC annually, of which 46% travels through the rivers of the humid tropics, i.e., about 250 TgC/yr (Meybeck 1993). The Amazon River alone transports an estimated 68 TgC/yr to the ocean (Kempe 1988), and 66% of the Amazon basin lies in one nation, Brazil. River basins in ecosystems within regions outside the tropics contribute the

remaining half of the global total, i.e., temperate forests and grasslands, 31%; boreal forests, 14%; savannah and sub-arid regions, 5%; and tundra, 4% (Meybeck 1993).

The fate of the riverine C is not totally understood. A portion is oxidized by heterotrophic respiration and thus returns to the atmosphere either directly from the river or estuaries or after entering the oceans. The C not oxidized goes into long-term storage in the sediments of the ocean bottom (although worldwide, rivers transport about 10% of this C into lakes [Meybeck 1993]). The amount of riverine C deposited in the ocean bottom as a sink is unknown, and therefore, is not accounted for in the C flux analyses for terrestrial ecosystems (Meybeck 1993).

If a significant portion of the 540 TgC/yr transported by the world's rivers is eventually found to be deposited in ocean sediments, it could explain up to 30% of the so-called "missing C" currently estimated to be 1800 Tg/yr (Sundquist 1993). Indeed, over 10% might be accounted for if the same results are found for just the 250 TgC/yr transported by tropical rivers.

Additionally, it is not clear if disturbances in terrestrial ecosystems significantly contribute to the transport of riverine C to ocean sinks, particularly from deforestation in the tropics. (J. Richey, Univ. Washington, pers. comm., 1993). However, since river drainage from the tropical ecosystems (largely forested ecosystems) is the highest among all global zones, estimates of the ocean sink for this riverine C could prove important for many national C flux estimates for the tropics (see Section VI.D.6). Though the estimated levels of river transported C are less for the temperate and boreal regions as noted above, the caveat applies there as well until additional data is available (see Maybeck 1993).

Box 1: Former Soviet Union

Before its dissolution, the former Soviet Union (FSU) was the largest country in the world. The FSU occupied one-sixth of the land surface of the Earth. The total land area of the FSU was 2240 X 10^6 ha. In 1983, the population of the FSU was 271.4 million. The former republics of the Soviet Union included Russia, Belorussia, Ukraine, Moldova, Baltic states (i.e., Lithuania, Latvia, and Estonia), Armenia, Georgia, Azerbaijan, Tajikistan, Turkmenistan, Uzbekistan, Kazakhstan, and Kyrgystan. Industrial carbon emissions in the FSU were between 0.998 PgC/ha (1988) (Subak et al. 1993) to 1.02 PgC/yr (1990) (Makarov and Bashmakov 1990).

The territory of the FSU is represented by a variety of climate conditions. The major part of the territory is in the boreal and temperate biogeographic zones. The climate in the FSU changes from arctic and subarctic in the north to warm temperate and desert in the south. From west to east, the climate makes a transition from maritime to continental to monsoon. Matthews (1983) identified eight principal types of vegetation in a global data base: forest, woodland, shrubland, grassland, tundra, desert, peatlands, and cultivated land. The vegetation of the FSU includes all of these major types (Kolchugina and Vinson 1991).

Arctic deserts and tundra formations are found in the northern regions of the FSU; deserts and semi-deserts occur in the southern regions. A vast area is occupied by forests. The total area of land under State forest management in 1983 was 1,259 X 10^6 ha (Vorobyov 1985) which is approximately 56.5% of the total area of the FSU. The FSU possesses 814 10^6 ha of forested land (Alimov et al. 1989) with most of this land in closed forest, or 28% of the area of closed forests of the world. A quarter of the world's growing stock of timber can be found in FSU. Seventy five percent of all FSU forests is coniferous boreal forests (i.e., needle-leaf or pine, larch, fir, spruce); 21% is deciduous softwood forests (e.g., aspen, poplar, linden, birch, except stony birch); the rest of the area is occupied by deciduous hardwood species (e.g., maple, beech, oak, stony birch). The terms deciduous softwood and deciduous hardwood species are commonly used in FSU to distinguish between deciduous species with wood of different density.

About 95% of the FSU forested area in the FSU is in Russia. Russia began to experience a high demand in timber in the 17th and 18th centuries; from the 1600s to 1814, 70 Mha of forest were cut in European Russia (Kolchugina and Vinson 1995). In the 19th century large scale logging began in Siberia. Immediately after the revolution in 1917, Russian forests were not under centralized management. The overall political and economical instability of the period resulted in an especially destructive use of forests. During the 1930s and 1940s, Siberian and northern European forests were extensively logged; these activities continued through the 1950s and 1960s (Kolchugina and Vinson 1995). After World War II, reforestation efforts were initiated throughout the FSU. Forest inventory data from 1966 to 1988 indicate that the area of forested land under State forest management in the FSU has remained at a stable level. At present, FSU forests are intensively exploited. The annual area of principal logging is approximately 2.0 10^6 ha.

The FSU has the greatest expanse of peatlands in the world (Tyuremnov 1976), estimated at 164.8 Mha (Botch et al. 1995; Kolchugina and Vinson 1994a).

A significant area of the FSU is underlain by continuous permafrost zone, estimated at 824.2 Mha (Kolchugina and Vinson 1993b,c). The continuous permafrost zone is approximately 40% of the FSU territory or 5% of the land surface area of the world.

Vast areas of the FSU are covered by grasslands, an important component of the terrestrial C cycle. Despite the fact that grasslands do not accumulate large quantities of plant mass compared with forest ecosystems, they exhibit high net primary productivity (NPP) (Bazilevich 1986) and, therefore, may influence the terrestrial C cycle.

III. Former Soviet Union Case Study

A. Objectives

The objective of the research presented herein was to provide an evaluation of the C cycle of terrestrial ecosystems of the FSU in the mid-late 1980s with special consideration given to forest ecosystems. The scope of work also included the estimate of C pools and fluxes of FSU non-forest ecosystems, including peatlands and agroecosystems. The C pools and fluxes of non-forest ecosystems were based on thematic maps and statistical data on peat and agricultural production. Forest statistical data were used to estimate net ecosystem productivity (NEP) of forest ecosystems and C flux associated with logging and forest fires.

B. Approaches

The C budget components of terrestrial ecosystems may be estimated using different approaches. For example, a number of ecoregions (i.e. relatively homogeneous regions with respect to phytomass, CWD, litter, NPP, and SOM densities per ha) may be isolated with thematic maps. When C values of phytomass, CWD, litter, NPP, and SOM are assigned to these ecoregions and the ecoregional estimates are aggregated, a calculation of the C budget components may be performed at the regional or national scale (Kolchugina and Vinson 1991, 1993a; Vinson and Kolchugina 1993). As another example, countries with significant timber resources typically have extensive forest statistical databases. Forest statistical data can be used to estimate the forest component of a C budget for the country; for instance, it can be related to phytomass and CWD estimates (Kolchugina and Vinson 1993d, 1993e).

These approaches have their advantages and disadvantages. The approach based upon thematic maps has the advantage of describing ecosystem types and geographical location of the ecosystem. Also, FSU scientists at more than a dozen leading institutes have accumulated data on C in soil and vegetation for several decades (Kazimirov and Morozova 1973; Aleksandrova 1977; Tytlyanova 1977; Vatkovskyi 1976; Dylis and Nosova 1977; Kazantseva 1980; Bazilevich 1986; Bazilevich et al. 1986; and others). These data combined with the areal extent of specific ecosystems identified with the help of thematic maps may serve as a basis for carbon pool and flux estimates. The main disadvantage is that most of these data do not describe specifics of carbon accumulation depending upon ecosystem age. Also, a limited number of site measurements is provided; hence, it is difficult to assess the spatial variation of carbon accumulation parameters.

An approach using forest statistical data has the advantage of containing an accurate assessment of commercial timber volume based on a large number of measurements, but no information is given with respect to ecosystem components (i.e., branches, roots, understory, shrubs) other than stem volume. Further, forest statistical data allow one to incorporate the age-class distribution of forest stands and estimated NEP. Use of all available data in a combination approach would undoubtedly result in the most comprehensive and possibly reliable estimate of the C budget. A combination approach is a long-term goal for C budget determination for the FSU.

C. Carbon Pools and Net Primary Production

The assessment of C pools of non-forest, natural (i.e., non-arable land) ecosystems and NPP of all natural ecosystems was based on the areal extent and density (per ha) of C pools and NPP of a specific ecosystem type. The assessment of C pools of

forest ecosystems and C pools and NPP of arable land was based on the statistical data.

1. Methods

Thematic maps were used to identify the area of the major biomes (complex of ecosystems within specific climatic belt or subbelt) in the FSU. The area of forest and non-forest ecosystems within the forest biomes was identified with the help of data on percent forest cover and forest statistical data on the areal extent of coniferous and deciduous forests.

a. Areal Estimates

About 95% of the territory of the FSU, including Russia, Ukraine, Belorussia, Moldova, Kazakhstan, and the Baltic states, was categorized with the help of a map showing soil-vegetation associations, i.e., ecosystems (Ryabchikov 1988) (Figure III.1). The main ecosystem types identified with the help of this map were the polar desert, tundra, forest-tundra/sparse taiga, taiga, mixed-deciduous forest, forest-steppe, and warm temperate woodlands, steppe, and desert-semidesert.

Because the FSU has a vast longitudinal extent, ecosystems with the same vegetation cover and soils may differ in carbon pools and productivity (e.g., densities of phytomass, CWD, litter, and NPP) depending on their geographical location. Consequently, eight georegions which reflect the geoclimatical dependence of C accumulation parameters were isolated in the FSU: West, Central, and Eastern European Parts; West, Central, and Eastern Siberia; Near-Ocean region; and Kazakhstan. The maps were superimposed using a Geographic Information System (GIS) to identify eco-regions (i.e., ecosystems presented on soil-vegetation map isolated within specific georegions) related to different soil-

Prepared for:
U.S.S.R. CARBON BUDGET PROJECT
U.S. Environmental Protection Agency
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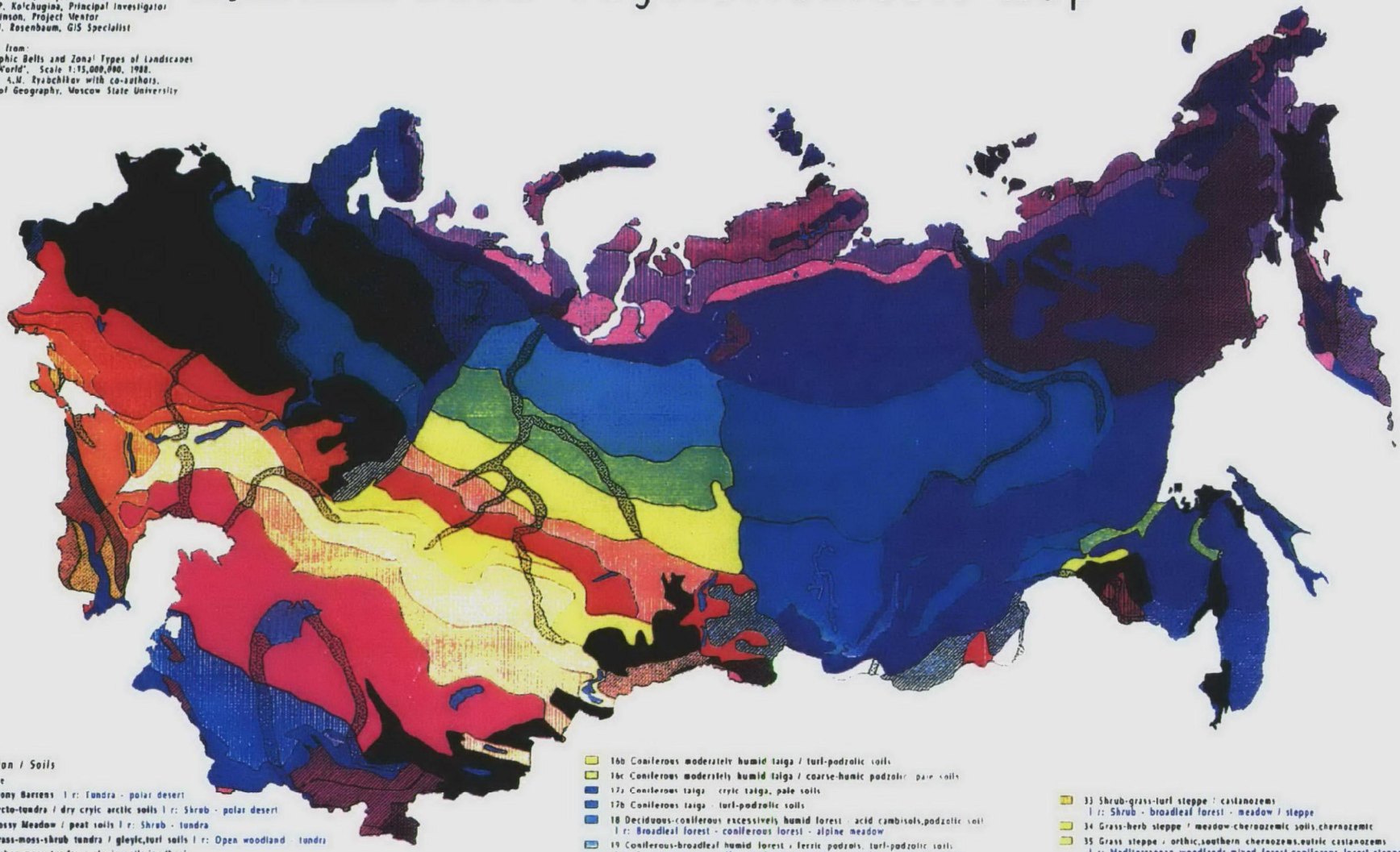
Digitized from:
"Geographic Belts and Zonal Types of Landscapes of the World", Scale 1:15,000,000, 1988.
By Prof. A.M. Ryabchikov with co-authors.
School of Geography, Moscow State University

Figure III.1. USSR Vegetation/Soil Map



Vegetation / Soils

- 1 Ice
- 2 Stony Barrens | r: Tundra - polar desert
- 3 Arcto-tundra / dry cryic arctic soils | r: Shrub - polar desert
- 4 Mossy Meadow / peat soils | r: Shrub - tundra
- 5 Grass-moss-shrub tundra / gleyic,turf soils | r: Open woodland - tundra
- 6 Lichen-moss tundra - gleyic soils,'podbur'
- 7 Shrub-moss,shrub tundra / peat podzolized soils,'podburs'
- 8 Shurb-meadow,small-leaf open woodlands - coarse humic-turf soils
- 9 Shrub, coniferous woodlands / gleyic-ferro-humic podzol,'podburs'
- 10 Coniferous ,shrub woodland / ferro-humic podzol,'podburs' | r: Taiga - meadow - tundra
- 11 Coniferous woodlands,ferro-humic podzols,'podburs' | r: Taiga - tundra
- 12 Grass-herb-shrub meadows / peat-turf soils | r: Coniferous forest - tundra
- 13 Meadow-taligrass,small-leaf open woodland/ turf soils, 'podburs' | r: Mixed forest - coniferous forest - tundra
- 14 Coniferous humid taiga ,illuvial humo-ferric podzols,'podburs' | r: Mixed forest - coniferous forest - shrub - meadow
- 15a Coniferous moderately humid taiga - illuvial ferro-humic,cryic podzols
- 15b Coniferous moderately humid taiga / turf-podzolic soils,ferro-humic podzols
- 15c Coniferous moderately humid taiga / podzolic soils, feric podzols
- 16a Coniferous moderately humid taiga - ferro-humic podzols,'podburs'
- 16b Coniferous moderately humid taiga / turf-podzolic soils
- 16c Coniferous moderately humid taiga / coarse-humic podzolic - pale soils
- 17a Coniferous taiga - cryic taiga, pale soils
- 17b Coniferous taiga - turf-podzolic soils
- 18 Deciduous-coniferous excessively humid forest - acid cambisols,podzolic soil | r: Broadleaf forest - coniferous forest - alpine meadow
- 19 Coniferous-broadleaf humid forest / ferric podzols, turf-podzolic soils | r: Forest-steppe - coniferous forest - meadow - tundra / alpine meadow
- 20 Broadleaf-coniferous humid forest - cambisols,turf-podzolic soils | r: Steppe - coniferous forest - tundra
- 21 Broadleaf-coniferous moderately humid forest - turf-podzolic soils | r: Steppe - coniferous forest - alpine meadow
- 22 Small-leaf-coniferous forest/subtaigas / turf-podzolic soils, grey luvisols | r: Steppe - mixed forest - meadow
- 23 Broadleaf humid forest / turf-podzolic soils, orthic cambisols | r: Steppe - coniferous forest - alpine meadow / meadow
- 24 Broadleaf moderately humid forests/turf-podzolic soils,grey luvisols,acid cambisols | r: Semidesert - coniferous forest - alpine meadow / meadow
- 26 Small-leaf-coniferous forest-steppe/podzolized and luvic chernozems, grey luvisols | r: Semidesert - open woodland - xerophytic meadow
- 27 Broadleaf forest-steppe and prairie - meadow chernozems, chernozemic soils
- 28 Broadleaf forest-steppe / grey luvisols,orthic and luvic chernozems
- 29 Decid.-conif. forest-steppe / grey luvisols, chernozemic soils, chernozems
- 30 Coniferous-small-leaf forest steppe / chernozems, eutric castanozems
- 31 Grass-herb steppe / orthic and southern chernozems | r: Deciduous forest - coniferous forest - alpine meadow/meadow
- 32 Grass steppe / orthic and southern chernozems
- 33 Shrub-grass-turf steppe / castanozems | r: Shrub - broadleaf forest - meadow / steppe
- 34 Grass-herb steppe / meadow-chernozemic soils,chernozemic
- 35 Grass steppe / orthic,southern chernozems,eutric castanozems | r: Mediterranean woodlands-mixed forest-coniferous forest-steppe-meadow
- 36 Shrub-grass-turf steppe - castanozems, solonetz
- 37 Grass-semismallshrub steppe / orthic, dystric castanozems
- 38 Smallshrub-grass semidesert / dystric castanozems,cambic vermosols
- 39 Shrub and smallshrub semidesert / dystric castanozems,cambic vermosols | r: Open woodland - steppe - meadow
- 40 Semishrub,shrub semidesert / cambic soils,orthic vermosols
- 41 Shrub,smallshrub semidesert,desert / cambic soils,orthic vermosols
- 42 Shrub desert / desert soils | r: Semidesert - steppe - desert
- 44 Unvegetated desert | r: Desert - semidesert - desert
- 60 Shrub-tree desert / sand, primative soils
- 61 Shrub,semismallshrub desert - red cambic, orthic and, dystric vermosols
- 65 Grass-shrub-smallshrub steppe / dystric cinnamonic soils
- Lakes
- Dry lake beds
- Riverine areas
- r: Altitudinal Spectrums of Mountain Landscapes (descriptive text in BLUE)

vegetation associations. Then, ecoregions were combined with site specific data on carbon accumulation parameters (Kolchugina and Vinson 1991; Vinson and Kolchugina 1993; Kolchugina and Vinson 1993a). Forest inventory data on percent forest cover (Vorobyov 1985; U.S.S.R. State Forestry Committee 1990) were used to estimate the areal extent of non-forest ecosystems within the forest biomes (Kolchugina and Vinson 1993d).

The exact area of coniferous and deciduous forests in FSU forest statistical data is provided for only 654 X 10^6 ha of FSU forests under the direct management of FSU. The ratio between the areas of coniferous and deciduous (separately hardwood and softwood) forests (reported for 654 X 10^6 ha) was applied to the areal extent of forest ecosystems (814 X 10^6 ha) estimated with the help of maps and statistical data on percent forest cover.

The estimate of the areal extent of peatlands (Table III.1) was based on the recent assessment by Botch et al. (1995 which considered the peatland type distribution, and data from FSU peat statistics. The area of agricultural land (cropland, pasture-lands, and haylands) was obtained from the World Resource Institute report (WRI 1992) and Kolchugina and Vinson (1994b).

b. Carbon Pools

Densities (per ha) of phytomass (Table III.2) and CWD (Table III.3) of the polar desert and tundra biomes, meadows and grassland ecosystems were obtained by correlating the data base on site-specific densities of total phytomass (aboveground and belowground) and CWD (aboveground and belowground) compiled by N.I. Bazilevich (1986) to the areal extent of ecoregions isolated with the GIS analyses. The data base on phytomass, CWD, litter, and NPP resulted from studies of approximately 1,500 vegetation complexes (sites) in the FSU. The data base is a comprehensive

Table III.1. Areas of Major Ecosystems and Land-Use Types of the FSU

Ecosystem/Land-Use Type*	Area ($X\ 10^6$ ha)
Polar desert	8.1†
Tundra (cold grasslands/small shrubs)	226.0†
Coniferous (needleleaf) forest (including sparse northern extreme)	610.7‡
Deciduous hardwood forest (oak, stony birch, etc.)	35.1‡
Deciduous softwood forest (birch, poplar, aspen, linden)	168.5‡
Cold meadows (partially tundra)	112.1‡
Boreal and temperate meadows (moderately moist)	297.9‡
Dry temperate grasslands	113.0†
Desert/semidesert	169.0†
Peatlands	164.8§
Arable land	227.0¶
Subtotal - nonforest ecosystems	1317.9
Subtotal - forest ecosystems	814.3
Total	2132.2

*Polar desert, tundra, grasslands, and desert from Ryabchinov 1988. Coniferous forest, deciduous hardwood forest, deciduous softwood forest, cold meadows, as well as boreal and temperate meadows from Ryabchikov 1988; Vorobyov 1985; and U.S.S.R. State Forestry Committee 1990. Peatlands from Botch et al. 1995. Arable land from Kolchugina and Vinson 1994b and WRI 1992.
†Based on Kolchugina and Vinson 1991.
‡Based on Kolchugina and Vinson 1993d; U.S.S.R. State Forestry Committee 1990; Ryabchikov 1988; Vorobyov 1985.
§Based on Botch et al. 1995.
¶Kolchugina and Vinson 1994b; WRI 1992.

Table III.2. Densities of Phytomass, FSU

Ecosystem/Land-Use Type*	Phytomass (MgC/ha)		
	Total	Above-ground	Below-ground
Polar desert	0.3†	0.2†	0.1†
Tundra (cold grasslands/ small shrubs)	8.7†	2.9†	5.8†
Coniferous (needleleaf) forest (including sparse northern extreme)	64.3‡	48.2‡	16.1‡
Deciduous hardwood forest (oak, stony birch, etc.)	63.6‡	50.9‡	12.7‡
Deciduous softwood forest (birch, poplar, aspen, linden)	48.5‡	38.8‡	9.7‡
Cold meadows (partially tundra)	11.2†	2.1†	9.1†
Boreal and temperate meadows (moderately moist)	6.7†	1.3†	5.4†
Dry temperate grasslands	6.0†	1.1†	4.9†
Desert/semidesert	5.1†	1.2†	3.9†
Peatlands	20.0†	10.0¶	10.0¶
Arable land	2.9§	0.5§	2.3§

*Polar desert, tundra, grasslands, and desert from Ryabchikov 1988. Coniferous forest, deciduous hardwood forest, deciduous softwood forest, cold meadows, as well as boreal and temperate meadows from Ryabchikov 1988; Vorobyov 1985; and U.S.S.R. State Forestry Committee 1990. Peatlands from Botch et al. 1995. Arable land from Kolchugina and Vinson 1994b and WRI 1992.

†Based on Bazilevich 1986 and Ryabchikov 1988. Density was weighted by area of different plant communities within each ecosystem type.

‡Obtained by dividing totals presented in Table III.6 by the ecosystems area (Table III.1).

§Based on Kolchugina and Vinson 1994b.

¶No data were available on aboveground and belowground allocation; phytomass was distributed equally above and below ground.

Table III.3. Densities of Coarse Woody Debris (CWD), FSU

Ecosystem/Land-Use Type*	CWD (MgC/ha)		
	Total	Above-ground	Below-ground
Polar desert	0.4†	0.3†	0.1†
Tundra (cold grasslands/ small shrubs)	12.4†	4.1†	8.3†
Coniferous (needleleaf) forest (including sparse northern extreme)	14.8‡	11.1‡	3.7‡
Deciduous hardwood forest (oak, stony birch, etc.)	14.6‡	11.7‡	2.9‡
Deciduous softwood forest (birch, poplar, aspen, linden)	11.2‡	9.0‡	2.2‡
Cold meadows (partially tundra)	15.5†	2.9†	12.6†
Boreal and temperate meadows (moderately moist)	6.2†	0.4†	5.8†
Dry temperate grasslands	6.2†	1.2†	5.0†
Desert/semidesert	4.8†	1.2†	3.6†
Peatlands	NA	NA	NA
Arable lands	0§	0§	0§

*Polar desert, tundra, grasslands, and desert from Ryabchikov 1988. Coniferous forest, deciduous hardwood forest, deciduous softwood forest, cold meadows, as well as boreal and temperate meadows from Ryabchikov 1988; Vorobyov 1985; and U.S.S.R. State Forestry Committee 1990. Peatlands from Botch et al. 1995. Arable land from Kolchugina and Vinson 1994b and WRI 1992.

†Based on Bazilevich 1986 and Ryabchikov 1988. Density was weighted by area of different plant communities within each ecosystem type.

‡Based on Kolchugina and Vinson 1993d, Yermolenko and Yermolenko 1982 and Bazilevich 1986.

§Based on Kolchugina and Vinson 1994b.

NA No data available.

source of information on common vegetation types in the FSU. Data on forest ecosystems given in Bazilevich (1986) do not reflect the forest age and, therefore, cannot be used directly for the assessment of the vegetation C pools, NPP, and NEP of FSU forests. The C content of plant mass was assumed at 50% (Kobak 1988).

Phytomass of FSU arable land was estimated from data on economical yields of major FSU crops applying harvest indexes (Gaston and Kolchugina 1994).

The estimate of phytomass and CWD of coniferous and deciduous forests was based on the forest statistical data (data on the total growing stock [GS]) (Alimov et al. 1989; U.S.S.R. State Forestry Committee 1990). Three major problems must be resolved when converting the volume of commercial timber to total forest plant mass. Specifically, one should account for (1) parts of trees other than stems, (2) ecosystem components other than trees, and (3) CWD accumulation. Sampson (1992) suggests the use of a multiplier of 0.53 to convert the volume of commercial timber (m^3) to total forest phytomass (MgC) (including roots, branches, and understory). Isayev et al. (1993) developed conversion factors specifically for FSU forests depending upon tree genera and forest age (these factors will be provided later in Table III.4). These conversion factors do not account for other ecosystem components than trees. Conversion factors developed by Isayev et al. (1993) were used herein with an addition of 3% for other-than-trees ecosystem components and assuming 50% of C in the plant mass. Density of phytomass was obtained by dividing the total phytomass of the coniferous and deciduous forests by their area. Density of CWD (Table III.3) was estimated based on the ratio of stem volume to aboveground CWD derived from FSU yield tables as described in Kolchugina and Vinson (1993e). The distribution of phytomass and CWD by above-

Table III.4. Accumulation of Phytomass and Coarse Woody Debris in FSU Forests

Class*	Species*	Average Age† (yrs)	Area* (X 10^6 ha)	Growing Stock* (GS) (X 10^6 m^3)	Net Increment of Stem Wood (NIW)‡ (X $10^6 m^3$/yr)	Conversion Factor (m^3 timber to CMg total forest phytomass) Assuming 50% Carbon in Plant Mass§	Net Accumulation of Phytomass (NAPh) (TgC/yr)	Net Accumulation of CWD¶ (NACWD) (TgC/yr)
Young I	Coniferous	10	48.0	675.1	67.51	0.44	29.77	1.75
	Hardwood	10	1.6	32.7	3.27	0.62	2.03	0.38
	Softwood	10	11.8	114.0	11.4	0.39	4.44	1.04
Young II	Coniferous	30	41.8	2401.8	90.70	0.44	39.99	6.45
	Hardwood	30	2.3	148.2	5.06	0.62	3.14	0.92
	Softwood	30	12.5	417.8	14.85	0.39	5.78	1.07
Middle Age	Coniferous	50	101.0	11837.0	301.68	0.37	112.67	33.23
	Hardwood	50	8.1	928.2	20.31	0.51	10.26	2.77
	Softwood	40	38.0	3641.3	118.56	0.39	45.86	6.58
Premature	Coniferous	70	49.7	7652.9	91.41	0.37	33.50	16.52
	Hardwood	70	3.2	359.1	-0.38	0.49	-0.19	0.71
	Softwood	60	13.0	1730.2	24.22	0.39	9.36	1.71
Mature/ Overmature	Coniferous	174	277.9	37999.4	218.56	0.38	82.93	16.15
	Hardwood	138	8.3	1048.7	7.62	0.51	3.89	1.06
	Softwood	67	37.1	5900.0	87.91	0.39	33.92	4.53
Subtotals	Coniferous		518.4	60566.2	769.85		298.87	74.10
	Hardwood		23.5	2516.9	35.88		19.14	5.84
	Softwood		112.4	11803.3	256.95		99.35	14.93
Total			654.3#	74886.4	1062.68		417.36	94.87

*Based on U.S.S.R. State Forestry Committee 1990 and Alimov et al. 1989.
†Species average age: coniferous, 113 yrs; hardwood deciduous, 79 yrs; softwood deciduous, 47 yrs (U.S.S.R. State Forestry Committee 1990).
‡See methodology (Section III.D.6, first approach).
§Based on Isayev et al. 1993; Bazilevich 1986; Kobak 1988.
¶Based on the decay rate applied to declining mortmass pool (i.e., amount decayed = [stock of deadwood]•[1 - decay rate]"9").
#The complete report is provided for 654.3; the total FSU forested area is 814.3. Estimates were extrapolated to the entire forested area.

and belowground parts was made according to Bazilevich (1986) and Yermolenko and Yermolenko (1982).

Average densities of litter and soil organic matter (SOM) of the polar desert, tundra, forest biomes, and grasslands (Kobak 1988) were weighted by the area of soil types (Ryabchikov 1988; Kolchugina and Vinson 1993a; Kolchugina et al. 1993) (Table III.5). Kobak (1988) provides data on over a hundred soil profiles (1 m depth) compiled from the review of approximately 70 published sources. Litter and SOM (i.e., peat) density of peatlands were obtained from Bazilevich (1986) and Botch et al. (1995. An entire peat thickness was considered. Area weighted average SOM C content of the arable land was calculated based on the distribution of soil types (Ryabchikov 1988) within FSU arable land (Cherdantsev 1961; Kolchugina et al. 1993). Mann (1986) developed an equation to predict current carbon content of cultivated soil as a function of the initial carbon content. The overall loss of 24% of the initial C content was estimated for current conditions of the arable land of the FSU (Gaston et al. 1993). The estimate was obtained by applying the equation of Mann to major soil types in the FSU.

c. Net Primary Production

The NPP densities of meadows, grasslands, and peatlands were obtained directly from Bazilevich (1986) (Table III.4). The NPP of croplands was assumed to be equal to their phytomass (Gaston and Kolchugina 1994).

The NPP density of coniferous, deciduous hardwood, and deciduous softwood forests was estimated with the help of Bazilevich (1986) data adjusted for the presence of young forest ecosystems using data on the age-class distribution reported in FSU forest statistical data (Kolchugina and Vinson 1993d). Bazilevich data

Table III.5. Densities of Litter, Soil Organic Matter (SOM), and Net Primary Productivity (NPP), FSU

Ecosystem/Land-Use Type	Litter (MgC/ha)	SOM* (MgC/ha)	NPP (MgC/ha/yr)
Polar desert	0.16†	50.0†	0.06#
Tundra (cold grasslands/small shrubs)	4.70†	200.0†	1.54#
Coniferous (needleleaf) forest (including sparse northern extreme)	15.30‡	120.0‡	2.70‡
Deciduous hardwood forest (oak, stony birch, etc.)	7.20‡	160.0‡	4.60‡
Deciduous softwood forest (birch, poplar, aspen, linden)	7.20‡	120.0‡	4.40‡
Cold meadows (partially tundra)	0.60†	150.0†	4.40#
Boreal and temperate meadows (moderately moist)	0.70†	185.0†	7.50#
Dry temperate grasslands	1.30†	292.0†	6.40#
Desert/semidesert	0.50†	45.0†	4.00#
Peatlands	16.90†	1299.0§	3.40#
Arable land	0	153.5¶	2.90¶

*For 1 m of mineral soils and for this entire thickness of peat.
†Based on Kobak 1988 and Ryabchikov 1988. Density was weighted by area of different plant communities within each ecosystem type.
‡Based on Kolchugina and Vinson 1993d.
§Based on Botch et al. 1995
¶Based on Kolchugina and Vinson 1994b.
#Based on Bazilevich 1986 and Ryabchikov 1988.

relate to established ecosystems (middle-age to overmature). Based on the information presented in forest statistical data (U.S.S.R. State Forestry Committee 1990), it was estimated that the ratio of established forest ecosystems (i.e., middle-age to overmature) to young forest ecosystems in the FSU is 4.5 to 1. Thus, for a total of 814 X 10^6 ha, an estimated 666 X 10^6 ha would be occupied by established forest ecosystems and 148 X 10^6 ha would be occupied by young forest ecosystems. Within the young forests, initial area-weighted average NPPs were decreased by a factor of four (this factor was derived based on the examination of FSU yield tables).

2. Results and Discussion

The largest area of the FSU was occupied by forest ecosystems and boreal/temperate herbaceous ecosystems (i.e., 38 and 32% of the total area of FSU terrestrial ecosystems, respectively) (Table III.1). Peatlands and polar desert/tundra ecosystems occupied 8 and 11% of the area, respectively. Desert/semidesert ecosystems accounted for 8% of the area. Arable land occupied 11% of the territory.

The estimate of the forested area was based on the information provided by the U.S.S.R. State Forestry Committee which is the best available source of information related to FSU forests. Kolchugina and Vinson (1993d), using the Ryabchikov (1988) map and data on percent forest cover, arrived at approximately the same result. It may be possible, however, that some of the low-productive and low-stocked northern forest ecosystems (especially in the forest-tundra zone) are omitted in the State forestry inventory. The area of peatlands reported herein (Table III.1) was twice the area estimated by Kolchugina and Vinson (1991) who based their assessment on the map (Isachenko 1988) which under-represents peatlands of the tundra zone and the Far East.

The total phytomass C pool of FSU terrestrial ecosystems was estimated at approximately 60.4 PgC with 41.1 PgC and 19.2 PgC above- and belowground, respectively (Table III.6). The total CWD C pool of the FSU was estimated at 19.3 PgC (10.4 and 8.9 PgC above- and belowground) or 30% of the total phytomass C pool (Table III.7). In polar desert and tundra, CWD exceeded that of phytomass. The total litter pool was estimated at 15.2 PgC, i.e., it was almost the same as the pool of CWD (Table III.8). The SOM C pool was estimated at 506 PgC. Major contribution was provided by peatlands (214.1 PgC).

Terrestrial ecosystems of the FSU contained 601.1 PgC. (Disagreement between the above and the value in Table VII.3 is due to rounding.) Phytomass (Table III.6), CWD (Table III.7), and litter C pools were 10.0% and 3.2%, and 2.5% of the total, respectively. The soil C pool accounted for 84.2% of the total C stored in FSU terrestrial ecosystems. FSU forests (almost all are in Russia) (49.6 PgC) accounted for 82.1% of the total terrestrial phytomass C pool and 59.1% (i.e., 11.4 PgC) of the total C pool of CWD. The NPP of FSU terrestrial ecosystems was estimated at 8.2 PgC.

D. Net Carbon Flux

The C flux between FSU forests and the atmosphere is determined by the difference between NEP, and C returned to the atmosphere through disturbances, i.e. forest fires, logging, and influence of pollutants, pests, and diseases.

1. Methods

The rate of C sequestration in undisturbed forest ecosystems was assumed to be equal to their NEP. The NEP equals net

Table III.6. Phytomass, FSU

Ecosystem/Land-Use Type*	Phytomass (TgC)		
	Total†	Above-ground†	Below-ground†
Polar desert	2.4†	1.6†	0.8†
Tundra (cold grasslands/ small shrubs)	1966.2†	655.4†	1310.8†
Coniferous (needleleaf) forest (including sparse northern extreme)	39268.0‡	29435.7‡	9832.3‡
Deciduous hardwood forest (oak, stony birch, etc.)	2232.4‡	1786.6‡	445.8‡
Deciduous softwood forest (birch, poplar, aspen, linden)	8172.3‡	6537.8‡	1634.5‡
Cold meadows (partially tundra)	1255.5†	235.4†	1020.1†
Boreal and temperate meadows (moderately moist)	1996.0†	387.3†	1608.7†
Dry temperate grasslands	678.0†	124.3†	553.7†
Desert/semidesert	861.9†	202.8†	659.1†
Peatlands	3296.0†	1648.0§	1648.0§
Arable land	635.6†	113.5†	522.1†
Total	60364.3	41128.4	19235.9

*Polar desert, tundra, grasslands, and desert from Ryabchikov 1988. Coniferous forest, deciduous hardwood forest, deciduous softwood forest, cold meadows, as well as boreal and temperate meadows from Ryabchikov 1988; Vorobyov 1985; and U.S.S.R. State Forestry Committee 1990. Peatlands from Botch et al. 1995 Arable land from Kolchugina and Vinson 1994b and WRI 1992.

†Obtained from the multiplication across data presented in Table III.1 and Table III.2.

‡Based on U.S.S.R. State Forestry Committee 1990, Isayev et al. 1993 (Table III.4), Bazilevich 1986, and Yermolenko and Yermolenko 1992.

§No data were available on aboveground and belowground allocation; phytomass was distributed equally above and below ground.

Table III.7. Coarse Woody Debris, FSU

Ecosystem/Land Use Type*	CWD (TgC)		
	Total†	Above-ground†	Below-ground†
Polar desert	3.2	2.4	0.8
Tundra (cold grasslands/small shrubs)	2802.4	926.6	1875.8
Coniferous (needleleaf) forest (including sparse northern extreme)	9038.4	6778.8	2259.6
Deciduous hardwood forest (oak, stony birch, etc.)	512.5	410.7	101.8
Deciduous softwood forest (birch, poplar, aspen, linden)	1887.2	1516.5	370.7
Cold meadows (partially tundra)	1737.6	325.1	1412.5
Boreal and temperate meadows (moderately moist)	1847.0	119.2	1727.8
Dry temperate grasslands	700.6	135.6	565.0
Desert/semidesert	811.2	202.8	608.4
Peatlands	NA	NA	NA
Arable land	0	0	0
Total	19340.1	10417.7	8922.4

*Polar desert, tundra, grasslands, and desert from Ryabchikov 1988. Coniferous forest, deciduous hardwood forest, deciduous softwood forest, cold meadows, as well as boreal and temperate meadows from Ryabchikov 1988; Vorobyov 1985; and U.S.S.R. State Forestry Committee 1990. Peatlands from Botch et al. 1995. Arable land from Kolchugina and Vinson 1994b and WRI 1992.

†Obtained from the multiplication across data presented in Table III.1 and Table III.3.

NA No data available.

Table III.8. Litter, Soil Organic Matter (SOM), and Net Primary Productivity (NPP), FSU

Ecosystem/Land-Use Type*	Litter† (TgC)	SOM† (TgC)	NPP† (TgC/yr)
Polar desert	1.3	405.0	0.5
Tundra (cold grasslands/small shrubs)	1062.2	45200.0	348.0
Coniferous (needleleaf) forest (including sparse northern extreme)	9343.7	73284.0	1648.9
Deciduous hardwood forest (oak, stony birch, etc.)	252.7	5616.0	161.5
Deciduous softwood forest (birch, poplar, aspen, linden)	1213.2	20220.0	741.4
Cold meadows (partially tundra)	67.3	16815.0	493.2
Boreal and temperate meadows (moderately moist)	208.5	55111.5	2234.3
Dry temperate grasslands	146.9	32996.0	723.2
Desert/semidesert	84.5	7605.0	676.0
Peatlands	2785.1	214075.2	560.3
Arable land	0	34844.5	658.3
Total	15165.4	506172.2	8245.6

*Polar desert, tundra, grasslands, and desert from Ryabchikov 1988. Coniferous forest, deciduous hardwood forest, deciduous softwood forest, cold meadows, as well as boreal and temperate meadows from Ryabchikov 1988; Vorobyov 1985; and U.S.S.R. State Forestry Committee 1990. Peatlands from Botch et al. 1995. Arable land from Kolchugina and Vinson 1994b and WRI 1992.

†Obtained from the multiplication across data presented in Table III.1 and Table III.5.

accumulation of phytomass (NAPh), net accumulation of CWD (NACWD), net accumulation of SOM (NASOM).

a. Non-Forest Ecosystems

The NAPh and NACWD were assumed to be zero for non-forest ecosystems of the FSU. These C pools were considered to be in equilibrium with atmospheric C.

The NASOM was represented by the rate of stable SOM formation. It was assumed that the accumulation of labile SOM is balanced by decompositional processes. Density of stable SOM accumulation was derived from data reported by Kobak (1988). For each vegetation type shown in Table III.1, a representative soil type was defined based on the Ryabchikov (1988) soil-vegetation map.

The rate of peat accumulation in FSU peatlands was based on estimates made by Botch et al. (1995). The research considered the rate of peat accumulation and the areal extent of every peatland zone of the FSU.

b. Forest Ecosystems

The presence of significant areas of "growing" forests (i.e. forests which have not reached the age when C accumulation is balanced by C emissions due to respiratory processes) is crucial for the existence of significant NEP. Forest age-structure is closely connected with the history of disturbances.

Disturbances to FSU forests were especially intensive at the end of the 19th century and continued through the mid-20th century (Kolchugina and Vinson 1994a). At present (1988), there is approximately 323 X 10^6 ha of young to premature forests reported for 654 X 10^6 ha of the forested area (Table III.4). However,

the total forested area of FSU is 814 X 10^6 ha; the total forested area of Russia is 771 X 10^6 ha (95%) (1988 Forest Inventory [U.S.S.R. State Forestry Committee 1990]). The mature (generally 80 to 100 yr, but may be younger) class refers to forests that have accumulated maximum timber and are eligible for commercial harvesting (Vorobyov 1985). The age of overmature forests may be greater than 160 yrs. FSU forests continue to sequester carbon beyond the age of technical maturity, e.g., larch forests accumulate wood for 100–130 yrs beyond their age of technical maturity (Kolchugina and Vinson 1993d).

The NAPh was estimated from the net annual increment of stem wood (NIW). The NIW of the young, middle-age, and premature (i.e., the category between middle-age and mature) forests was estimated as the difference of the GS densities (per ha) of a given and preceding age-class divided by the difference in age and multiplied by the area of a given age-class. The NAPh was estimated using multipliers given by Isayev et al. (1993) to convert m^3 of stem wood to Mg of total tree phytomass. Three percent was added to account for content C for other than main story ecosystem components. Carbon of plant mass was assumed at 50% (Kobak 1988) (Table III.4).

The NACWD was estimated from data on (1) the ratio of accumulated CWD in coniferous, hardwood, and softwood deciduous forests to their GS (FSU yield tables [Kozlovski and Pavlov 1967]), and the ratio is dependent on the site quality and age of the forest; (2) the age-class distribution of growing stock (GS); (3) the distribution of forests by site-quality (1988 Forest Inventory [Vorobyov 1986; U.S.S.R. State Forestry Committee 1990]); and (4) the application of a two percent per year decomposition rate for coniferous and hardwood deciduous forests and six percent decomposition rate for softwood deciduous forests (M. Harmon, pers. comm., 1993). This approach did not account for decomposition of residue from previous disturbances.

Because the difference in the average age between the mature/overmature and premature forests may be very large, another method was used to estimate NIW for these forests. The mature/overmature category includes all forests which are older than the age at which forests are eligible for principal cutting (i.e., industrial cuttings other than thinnings and sanitary cuttings) (as reported by the U.S.S.R. State Forestry Committee 1990; Alimov et al. 1989). The mature/overmature forests include a variety of forest stands: (1) the even-age forests which are approximately 80-100 years and older (for the softwood deciduous forests the age of principal cutting may be designated at a much earlier date, e.g., 60 years and earlier) and (2) the uneven-age very old primary forest ecosystems ("old" is a relative term and refers to the fact that these forests have reached the successional stage when they can be described as "climax" forests [Odum 1953]).

The GS density of the old even-age forests and uneven-age forests may be significantly lower than the GS density of the premature forests because of the natural environmental conditions (climate, soils, elevation, etc.) under which these stands were developing. For example, in Siberia there is a vast expanse of the uneven-age forests which are included into the category of the mature/ overmature forests with a relative low GS density. Unfortunately, at the present time, there are no available data on the exact areal extent and the average age of these two groups within the mature/overmature forests. Two different approaches were used to estimate NAPh and NACWD of the mature/overmature forests.

Under Approach I, the average age of the mature/overmature forests was estimated from the data on the areal extent of forest age-classes, the average age of every age-class, and the average age of FSU forests (U.S.S.R. State Forestry Committee 1990) (Table III.8). Accumulation of timber continues at the average age estimated for the mature/overmature forests (Kozlovskyi and

Pavlov 1967). The NAPh of the mature/overmature forests was estimated by dividing their GS by the average age and applying conversion factors. This procedure may overestimate the current rate of NAPh for old forests (Kozlovsky and Pavlov 1967). The NACWD was estimated using the same methodology applied for other age-classes.

The first approach used to estimate NAPh and NACWD of the mature/overmature forests (Approach I) was based on the assessment of the average age of this forest category, which was established from data on the average age and the age-class distribution of FSU forests. However, it is difficult to assess precisely the average age of FSU forests for the reasons presented above (i.e., a presence of the uneven-age forests). A second approach (Approach II) was used to assess NPAh and NACWD of the mature/overmature forests, and it did not rely on the data on dynamics of the GS of the mature/overmature forests in 1983 and 1988 reported by the U.S.S.R. State Forestry Committee (Alimov et al. 1989).

The data reported by Alimov et al (1989) allow one to estimate the difference in the GS of the mature/overmature forests between 1983 and 1988 (i.e., a 5 year period). It is important to remember that principal cuttings take place specifically in the mature/overmature category of forests (by definition of this forest age category). Therefore, the difference in the GS of the mature/overmature forests between 1983 and 1988 reflects the dynamics of timber growth, principal cuttings, and other disturbances which took place during the period considered. This approach assumes inventory procedures are consistent across time and that equivalent forest areas are treated at each point in time.

Considering (1) the difference in the GS of the mature/ overmature forests between 1983 and 1988, (2) the rate of principal

cuttings during this period, and (3) the forested areas included in the 1983 and 1988 inventories, the rate of phytomass accumulation/loss (from other reasons than principal cuttings) was estimated (separately for the coniferous, hardwood deciduous, and softwood deciduous forests). It should also be noted, that the U.S.S.R. State Forestry Committee (Alimov et al. 1989) reports data for only 654 X 10^6 ha (the area under the direct management of the Federal Government). The final results must be adjusted to the total forested area of 814 X 10^6 ha.

The NASOM was assessed separately for the young-to-premature and the mature/overmature forests. In mature/overmature forests, NASOM was considered to be represented by the rate of stable soil organic matter formation and was estimated as previously described. In young-to-premature forest ecosystems, an additional accumulation of labile soil organic matter was assumed. The total accumulation of SOM of forest ecosystems (labile and stable) was estimated at approximately 0.1 MgC/ha/yr (Kolchugina and Vinson 1993a).

c. Disturbances

Approximately 2.5 X 10^6 ha of forests are burned and reported annually in areas of active monitoring, which amount to 64% of the total area under the State forest management. The total burned area is larger (i.e., 3.5 X 10^6 ha in 1991 and includes non-forest ecosystems (Korovin 1993). A larger burned area of 10.0 X 10^6 ha/yr for Central Siberia alone was obtained from satellite system remote sensing data (Stocks 1991). However, these data may misrepresent forest fires in the observed area because the State Forest Inventory reports only 1.67 X 10^6 ha of forest fires in Siberia for the same period (Izrael and Rovinskyi 1990).

Forest fires cause an immediate C efflux to the atmosphere from burned plant mass, litter (forest floor), and SOM. Later, mortality, soil respiration, and decomposition of killed (but not burned) trees may cause additional C emissions (Auclair 1985; Agafonov 1989). The C loss in an ecosystem depends on the type of site, location, and the intensity of forest fire (Phalaleyev 1985; Kurbatskyi and Tsykalov 1988). An intense fire may deplete the volatile nutrients in the soil (Raison et al. 1985) and inhibit growth of vegetation in the post-fire period, however, in some instances a decrease in C content may occur in the uppermost soil layer with no significant change in the lower mineral horizons.

A pyrogenic enhancement of forest growth is often observed after fires of low intensity, owing to mineralization of organic matter, mobilization of nutrients in soils, thermal amelioration (especially in areas with severe climatic conditions, e.g., the permafrost zone), and natural selection of woody plants with high growth rates. In light-crown coniferous forests (larch and pine), fire opens the crown, allowing shade-intolerant young growth to reach the canopy. The bark of these trees helps to resist fires of low intensity (Phalaleyev 1985; Johnson 1992).

Even though there is no strong scientific evidence that the extent of forest fires in the FSU is significantly greater than officially reported, this possibility should not be excluded. Light-crown coniferous forests accumulate fuel that is available for combustion every 30 to 40 yr (Phalaleyev 1985), so a 40-year return interval was assumed.

The areas of pine and larch forests are 120 X 10^6 ha (GS density 125 m^3/ha) and 258 X 10^6 ha (GS density 100 m^3/ha), respectively (Vorobyov 1986). The forest plant mass densities are 55 MgC/ha and 44 Mg C/ha, respectively (using multipliers of 0.37 (Table

III.4) to convert m^3 of timber to ecosystem Mg C and 1.19 to account for mortality (phytomass to CWD ratios, see Tables III.2 and III.3, coniferous forests). It was assumed that during low-intensity understory fire with a 40-yr frequency, 10% of the total plant mass is burned. This corresponds to 45 TgC/yr for the total fire area of 9.5 X 10^6 ha. The probability of post-fire emissions is low, since little damage occurred; on the contrary, fire could enhance plant mass accumulation by opening space for young trees and mobilizing nutrients.

Fire monitoring may register only large crown fires which are predominant in dark-crown coniferous forests (e.g., "cedar"-pine [*Pinus sibirica, P. koraiensis*] and also fir and spruce). The total stock of phytomass, CWD, and SOM available for combustion would be approximately 31 TgC/yr, 6 TgC/yr, and 20 TgC/yr, respectively. These values were calculated considering (1) the GS of dark-crown coniferous forests of 138 m^3 ha, (2) conversion factors presented above, (3) average soil carbon density 136 MgC/ha (Kolchugina and Vinson 1993a), (4) 25% of SOM would be lost (the selection of this value was based on literature review [Kurbatskyi and Tsykalov 1988; Phalalevev 1985; Nikodimov 1988; Furyaev 1989; Johnson 1992]), and (5) the fact that 0.6 X 10^6 ha of large forest fires are annually registered in FSU official data. The total direct C emissions were estimated at 57 TgC/yr. In this case, a post-fire effect is possible, but very little plant mass is available for additional decomposition under an assumption made herein that fire consumes the entire stock of phytomass and CWD.

In exposed soils with a 10°C temperature increase, decomposition of belowground CWD and SOM may be 2.4 times greater (Raich and Schlesinger 1992). The emissions of C from the soil surface associated with decomposition of belowground CWD, litter, and SOM in FSU taiga forest ecosystems under normal temperatures was estimated at 2 MgC/ha/yr on average

(Kolchugina et al. 1993). To estimate the upper level of post-fire emissions, it was assumed that no regrowth of vegetation occurs and rates of decomposition in exposed soil are higher during the 10-yr period after a fire within 0.6 X 10^6 ha subjected to intense crown fires. The total post-fire emissions were estimated to be 3 TgC/yr. This is a very rough approximation because the exposure to sun may inhibit decomposition processes by increasing temperatures and decreasing moisture content to an extent that limits microbial growth.

From the 1960s through the 1980s, timber production in the FSU remained at a constant level of 380.8—411.5 Mm^3/yr (Vorobyov 1986, 1985). It is reasonable to assume that carbon was accumulating in long-term wood products. From 389 Mm^3/yr of wood harvested in 1987-1989 (WRI 1992), 84 Mm^3/yr was burned, and 305 Mm^3/yr was used as sawnwood, panels, and paper products. This represents 148 TgC/yr, considering a conversion factor of 0.38 (for the prevailing coniferous and soft deciduous stands, Table III.4) to convert m^3 of timber to MgC of ecosystem phytomass, including slash carbon. Wood products accounted for 79 TgC/yr (conversion factor 0.26 to convert m^3 of timber to MgC). Melillo et al. (1988) estimated carbon effluxes from the decay of 10- to 100-yr living products at 46 TgC/yr; the net accumulation of wood products, therefore, was estimated at 33 TgC/yr. This amount was subtracted from the estimate of total carbon associated with phytomass of ecosystems subjected to logging. Net carbon emissions from forest logging were estimated at 115 TgC/yr.

Industrial pollution in the FSU is localized; in 1989, 0.107 X 10^6 ha of the FSU forests were killed by different pollutants (U.S.S.R. Committee for Protection of Nature 1989). Approximately 0.039 X 10^6 ha/yr of forests were killed by pests, diseases, and wild animals. The total area severely affected, but not killed by pollutants, pests, and diseases is 3.0 X 10^6

ha; an additional 0.14 X 10^6 ha of forests were cleared for purposes other than commercial timber production (U.S.S.R. Committee for Protection of Nature 1989; Izrael and Rovinskyi 1990). The decrease in productivity of affected forest ecosystems was ignored herein because this area is only 0.4% of Russian forests. Besides, forests affected by pollutants, pests, and diseases are the primary target for fires. Therefore, it may be assumed that the productivity loss in forests affected by pollution, pests, and diseases may be accounted for in forest fire emissions. Loss in productivity may also be accounted for in forest statistical data.

2. Results and Discussion

In the mid-to-late 1980s, non-forest terrestrial ecosystems were a source of C to the atmosphere, while forest ecosystems acted as a net sink for atmospheric C in the FSU.

a. Non-Forest Ecosystems

The total NASOM of non-forest ecosystems was estimated at 5.3 TgC/yr (Table III.9). Considering peat accumulation (52.7 TgC/yr), and burning (200 Tg of peat as dry organic matter, or 100 TgC) the total loss from peat accumulation/burning was 47.3 TgC/yr (C efflux).

At present, the arable land of the FSU is losing 94.2 TgC/yr due to mineralization of SOM and soil erosion, respectively (Kolchugina and Vinson 1994b).

b. Forests

Using Approach I and data from Table III.4, the NAPh of 814 X 10^6 ha forest ecosystems in the FSU was estimated at 519.5

TgC/yr (Table III.9). The NACWD was estimated at 118.1 TgC/yr. The NASOM was estimated at 40 TgC/yr. Density of NAPh, NACWD, and NASOM of FSU forests (Table III.10) was obtained by dividing total NAPh and NACWD (Table III.9) by the area of specific forest types (Table III.1). The sequestration potential or NEP of FSU forests—if they were left undisturbed—was estimated at 0.678 PgC/yr and consistent with assessment made by Bonan (1991a). Russian forests represent 95% of the total NEP of the FSU. Previously NEP of FSU forests was estimated at 0.83 PgC/yr (Kolchugina and Vinson 1993d) and 0.88 PgC/yr (Kolchugina and Vinson 1993e). The first assessment was based on the assumption that forests in the FSU are fully stocked and did not consider CWD accumulation/decomposition. The second assessment ignores CWD decomposition in undisturbed forest ecosystems. Because the present estimate is based on the results of the 1988 Forest Inventory (the Inventory is conducted every decade for the area under State management), it reflects the age, quality, and stocking of FSU forests as well as losses of forest productivity owing to forest fires or the influence of pests, diseases, and pollutants. However, the precise assessment of the average age of FSU forests may represent a problem. Losses of phytomass, CWD, litter, and soils burned directly as well as post-fire emissions are not included in forest statistical accounting.

Using Approach II to estimate NAPh and NACWD for the mature/overmature forests, it appeared that in 1983 the GS of the coniferous mature/overmature forests reported for 654 X 10^6 ha was 40,856 Mm^3, but it was only 37,999 Mm^3 in 1988 (Alimov et al. 1989). Therefore, between 1983 and 1988 the GS of the coniferous mature/overmature category of FSU forests decreased by 2,856 Mm^3. However, according to the U.S.S.R. State Forestry

Table III.9. Net Accumulation of Phytomass (NAPh), Coarse Woody Debris (NACWD), and Soil Organic Matter Accumulation (NASOM), FSU

Ecosystem/Land-Use Type*	NAPh (TgC/yr)		NACWD (TgC/yr)		NASOM (TgC/yr)
Approach†	I	II	I	II	
Polar desert	0		0		0
Tundra (cold grasslands/small shrubs)	0		0		0.5§
Coniferous (needleleaf) forest (including sparse northern extreme)	372.0‡	96.0‡	92.2‡	240.7‡	20.8¶
Deciduous hardwood forest (oak, stony birch, etc.)	23.8‡	37.6‡	7.3‡	10.9‡	1.5¶
Deciduous softwood forest (birch, poplar, aspen, linden)	123.7‡	119.0‡	18.6‡	8.3‡	5.7¶
Cold meadows (partially tundra)	0		0		0.6¶
Boreal and temperate meadows (moderately moist)	0		0		3.3§
Dry temperate grasslands	0		0		0.8§
Desert/semidesert	0		0		0.2§
Peatlands	0		0		52.7#
Arable land	0		0		-94.2▲
Total	519.5‡	252.6‡	118.1‡	269.9‡	-8.2

*Polar desert, tundra, grasslands, and desert from Ryabchikov 1988. Coniferous forest, deciduous hardwood forest, deciduous softwood forest, cold meadows, as well as boreal and temperate meadows from Ryabchikov 1988; Vorobyov 1985; and U.S.S.R. State Forestry Committee 1990. Peatlands from Botch et al. 1995. Arable land from Kolchugina and Vinson 1994b and WRI 1992.

†Two different approaches (described in Section III.D.1.b) were used to estimate NAPh and NACWD of the mature/overmature forest ecosystem.

‡Based on Alimov et al. 1989; U.S.S.R. State Forestry Committee 1990; Isayev et al. 1993 (see methodology, Section III.D.1.b)

§Based on Kobak 1988 and Ryabchikov 1988.

¶Based on Kolchugina and Vinson 1993d.

#Based on Botch et al. 1995.

▲Based on Kolchugina and Vinson 1994b.

Table III.10. Densities of Net Accumulation in Phytomass (NAPh), Coarse Woody Debris (NACWD), and Soil Organic Matter Accumulation (NASOM), FSU

Ecosystem/Land-use Type*	NAPh (MgC/ha/yr)		NACWD (MgC/ha/yr)		NASOM (MgC/ha/yr)
Approach†	I	II	I	II	
Polar desert	0		0		0.001‡
Tundra (cold grasslands/ small shrubs)	0		0		0.002‡
Coniferous (needleleaf) forest (including sparse northern extreme)	0.61†	0.16†	0.15†	0.39†	0.034†
Deciduous hardwood forest (oak, stony birch, etc.)	0.68†	1.0†	0.21†	0.31†	0.042†
Deciduous softwood forest (birch, poplar, aspen, linden)	0.73†	0.71†	0.11†	0.11†	0.034†
Cold meadows (partially tundra)	0		0		0.005‡
Boreal and temperate meadows (moderately moist)	0		0		0.011‡
Dry temperate grasslands	0		0		0.007‡
Desert/semidesert	0		0		0.001‡
Peatlands	0		0		0.320§
Arable land	0		0		-0.415¶

*Polar desert, tundra, grasslands, and desert from Ryabchikov 1988. Coniferous forest, deciduous hardwood forest, deciduous softwood forest, cold meadows, as well as boreal and temperate meadows from Ryabchikov 1988; Vorobyov 1985; and U.S.S.R. State Forestry Committee 1990. Peatlands from Botch et al. 1995. Arable land from Kolchugina and Vinson 1994b and WRI 1992.

†Two different approaches were used to estimate NAPh and NACWD of the mature/overmature forest ecosystems. Obtained by dividing NAPh, NACWD and NASOM totals (Table III.9) by the area of ecosystems/land-use types (Table III.1).

‡Based on Kobak 1988 and Ryabchikov 1988.

§Based on Botch et al. 1995.

¶Obtained by dividing NASOM total (Table III.9) by the area of arable land (Table III.1).

Committee (Alimov et al. 1989), the area of the coniferous forests included in the 1988 inventory decreased by 0.7 X 10^6 ha compared to the 1983 inventory, which corresponds to a difference of 95.2 Mm^3 (assuming the average density of the GS of the mature/ overmature forests at 136 m^3/ha [Table III.4]). This volume was assumed to have remained on the forest land base. Thus, for the equivalent area, the annual loss of the GS of the coniferous mature/overmature forests was 552.1 Mm^3/yr, or 687.2 Mm^3/yr estimated for 814 X 10^6 ha. Between 1983 and 1988, the average rate of principal cuttings of the coniferous forests was 233.4 Mm^3/yr. Therefore, between 1983 and 1988, for the equivalent area, there was a loss of 453.8 Mm^3/yr of standing timber which was independent of principal cuttings (i.e., caused by natural mortality or other than logging disturbances). This loss of the GS corresponded to 172.5 TgC/yr (assuming 0.38 conversion factor for the coniferous stands [Table III.8]). This loss of C was assumed to result in the formation of a new pool of CWD. The decomposition of CWD may be assumed at 2%/yr (as for the coniferous stands). Thus, the NACWD in the mature/overmature forests was estimated at 169 TgC/yr.

In 1983, the GS of the hardwood deciduous mature/overmature forests was 977 Mm^3, and it was 1,049 Mm^3 in 1988 (reported for the area of 654 X 10^6 ha) (Alimov et al. 1989). In 1988, the area included in the inventory was 0.1 X 10^6 ha lower than in 1983. The decrease in the inventoried area of the hardwood deciduous forests may account for 12.6 Mm^3 decrease in the GS (assuming 126.4 m^3/ha the GS density [Table III.8]). Therefore, between 1983 and 1988, for the equivalent area, the GS of the hardwood deciduous mature/overmature forests actually increased by 84.6 Mm^3 (5 years), which corresponded to 21.1 Mm^3/yr estimated for 814 X 10^6 ha. Between 1983 and 1988, the average rate of principal cuttings of the hardwood deciduous forests was 17.0 assuming Mm^3/yr. This value was calculated from the data assuming total volume of deciduous timber logged (95.2 Mm^3/yr)

and the relative areas of the hardwood and softwood deciduous forests (1:4.6) (Alimov et al. 1989). Between 1983 and 1988, standing timber increased by 38 Mm^3/yr (before logging). This corresponded to NAPh of 18.6 TgC/yr (assuming 0.49 conversion factor for the hardwood deciduous stands [Table III.4]). Furthermore, NACWD may be assumed at 27% of HAPh (Table III.4; middle-age forest category), or 5.0 TgC/yr.

In 1983, the GS of the softwood deciduous mature/overmature forests was 5,819 Mm^3 and 5,900 Mm^3 in 1988 (reported for 654 X 10^6 ha) (Alimov et al. 1989). The area included in the 1983 and 1988 inventories was similar. Therefore, between 1983 and 1988, the GS of the softwood deciduous mature/overmature forests actually increased by 80.9 Mm^3, which corresponded to 20.2 Mm^3/yr estimated for 814 X 10^6 ha. Between 1983 and 1988, the average rate of principal cutting of the softwood deciduous forests was 78.2 Mm^3/yr. Between 1983 and 1988, the standing timber increased by 98.4 Mm^3/yr (before cuttings), which corresponded to NAPh of 38.4 TgC/yr (assuming 0.39 conversion factor for the softwood deciduous stands [Table III.4]). Furthermore, NACWD may be assumed at 14% of NAPh (Table III.4; middle-age category), or 5.4 TgC/yr.

Using Approach II, the NAPh of the coniferous and deciduous mature/overmature FSU forests was estimated at -115.5 TgC/yr and the NACWD of these forests was estimated at 179.0 TgC/yr. The NAPh of the young, middle-age, and premature FSU forests (determined under Approach I) was estimated at 369.2 TgC/yr (estimated for 814 X 10^6 ha) and the NACWD of these forests was estimated at 91.0 TgC/yr. Thus, the total NAPh of the FSU forests was 253.7 TgC/yr and the total NACWD was 270.0 TgC/yr. Approach II relied on a correct representation of the GS volume of the mature/overmature forests in 1983 and 1988. The loss of 453.8 Mm^3/yr is equivalent to the area of approximately 3.3 X 10^6 ha. The loss of the GS of the coniferous mature/overmature

forests may be explained by several reasons, e.g., natural mortality of the even-age old forests, dieback from pests, diseases, fires, windfalls, etc.

The decrease in the GS of the mature/overmature coniferous forests which was not attributed to logging could also be associated with the fact that between 1983 and 1985 the area of the even-age old forests with mortality (but which still have growing trees) increased and these forest stands were not included in the inventory of commercial timber. Furthermore, forests subjected to forest fires and diseases or attacked by insects and, as a result, containing large number of dead trees or trees with burn-marks could also be excluded from the inventory. In addition, under-reported logging could account for some decrease in the GS of the mature/overmature forests.

The direct fire emissions from low-intensity understory fires were estimated at 45 TgC/yr for the total burned area of 9.5 X 10^6 ha. The replenishment of this phytomass may be quick enough to make the emission only a short-lived efflux. The direct fire emissions within 0.6 X 10^6 ha of intense crown fires were estimated at 57 TgC/yr. Post-fire emissions were estimated at 3 TgC/yr. Thus total fire emissions were estimated at 105 TgC/yr. The overall release from logging related to wood and slash burned, plus slash and wood products decomposition was 115 TgC/yr.

In the mid-1980s, FSU forests were a net sink for 0.343-0.458 PgC/yr of atmospheric C (Table III.11). The difference in the assessment of the net C flux associated with FSU forests (natural ecosystems, disturbances, and wood products) was substantial (127 TgC/yr) and was associated with the uncertainty in the estimates of the NEP of the mature/overmature age-class. More data on the GS, age distribution, and the description of disturbances for the mature/overmature category of FSU forests are needed for the

Table III.11. Summary: Carbon Pools, Fluxes, Net Sequestration, and Emissions, FSU

Carbon	PgC	PgC/yr		(-) PgC/yr
Pools				
Phytomass	60.4			
Coarse woody debris (CWD)	19.3			
Litter	15.2			
Soil organic matter (SOM)	506.0			
Subtotal	601.1			
Fluxes				
Net primary productivity		8.2		
Net Accumulation (Sequestration)				
Forest ecosystems				
Approach		I	II	
Phytomass		0.520	0.253	
CWD		0.118	0.270	
SOM (labile, stable)		0.040	0.040	
Subtotal		0.678	0.563	
Non-forest ecosystems				
Peat		0.053		
Soil		0.005		
Subtotal		0.058		
Total		0.736	0.621	
Emissions				
Forest ecosystems/disturbances				
Fires				(0.105)
Logging				(0.115)
Subtotal				(0.220)
Nonforest ecosystems				
Arable land (soil)				(0.094)
Peat utilization				(0.100)
CH_4 from peatlands				(0.030)
Subtotal				(0.224)
Industrial				(1.020)
Total				(1.464)
Net flux (sequestration and disturbance in terrestrial ecosystems, as well as industrial emissions)				0.728-0.843
Net flux (sequestration and disturbance in terrestrial ecosystems)		0.292-0.177		
Net flux forest (sequestration and disturbance in forest ecosystems)		0.458-0.343		

improved assessment of the carbon flux within this age-class. These estimates are within the range previously reported for FSU forests (0.4-0.5 PgC/yr) (Sedjo 1992; Kolchugina and Vinson 1993d,e; Kolchugina and Vinson 1994a). Kolchugina and Vinson (1993d) over-estimated stocking of FSU forests. Kolchugina and Vinson (1993e) used data on the total mean annual increment reforested by the U.S.S.R. State Forestry Committee, and they reported data (1994a) obtained by utilizing Approach I presented herein. The present estimate was greater than estimates made by Melillo et al. (1988) and Krankina and Dixon (1993) who did not consider the age-structure of Russian forests. The net C sink for FSU forests exceeded the net C sink estimated for Canadian forests (Kurz and Apps 1993). The area of 20- to 60-yr FSU forests (maximum rate of C sequestration) is 265 X 10^6 ha, i.e. 1.7 times the area of the same age-group in Canada. Terrestrial ecosystems of the FSU were a net sink for 0.177-0.293 PgC/yr (Table III.11). Methane emissions from industrial processes and peatlands (Kolchugina and Vinson 1994a) amount to 56 TgC/yr. Emissions of chlorofluorocarbons are insignificant (WRI 1992; Subak et al. 1993).

Russian forests accounted for 95% of the net sink of C estimated for FSU forests. In the 1990s, logging of Russian forests was only half as intensive as in the 1980s (Korovin, pers. comm., 1994). The C emissions associated with logging may thus be reduced significantly. At present, Russian industrial emissions are 0.7 to 0.8 PgC/yr (Karaban et al. 1993). Currently, Russian forests may be offsetting approximately 43% of the national industrial emissions.

E. Forest Management Options for Mitigating Carbon Emissions

At present, it is possible to provide only expert assessment of forest management options available in the FSU (Shvidenko and Rozhkov, pers. comm., 1992).

1. Reforestation

It is possible to afforest 95 X 10^6 ha of currently unforested area under the jurisdiction of the federal government (from 145 X 10^6 ha theoretically available for reforestation). This option would provide a net sequestration of 0.18 PgC/yr (an average of 1.9 MgC/yr).

2. Increased Fire Control and Prevention

The extent of forest fires could be decreased by 50%. Forest fires in the FSU are a natural occurrence in forest ecosystems. Fire control and prevention may cause an accumulation of a significant amount of fuels available for burning, thus leading to catastrophic fires. Hence, the feasibility of this management option should be investigated further.

3. Enhanced Forest Productivity

This goal could be achieved mainly by reconstructing low-stocked stands and partial replacement of deciduous stands with long-rotation conifers. It may be possible to reconstruct 140 X 10^6 ha of low-stocked stands in the FSU and replace 60 X 10^6 ha of deciduous stands (low productive, small leaf, deciduous forests) in the European Part of the FSU. However, the replacement of deciduous stands by conifers may present a serious problem for FSU (Russian) forests. Deciduous and mixed stands may be more

resistant to pests, diseases, and fires, than coniferous stands, especially monoculture stands. The issue on the replacement of old-growth forests by young forest plantations is also questionable considering the large quantities of coarse woody debris stored in mature and over-mature forest ecosystems compared to young forests.

4. Improved Disease and Pest Control

This measure would include the decrease and subsequent elimination of the pests and diseased areas, removal and selective cutting of dead and sick trees, etc. This option may help to prevent fires and decrease C emissions.

5. Reconstruction of the Forestry Industrial Sector

The reconstruction includes a transition to ecologically protective methods of wood harvesting that would allow rapid regeneration of forest stands and an increase in efficiency of wood utilization from 50 (present assessment) to 70%. This is a very significant management option. At present, forest phytomass is utilized (efficiency of logging) at levels between 30 to 70% of the total. Poor extraction of timber causes overcutting of significant forest areas in the FSU. It would be a better use of forest resources designated for logging to reduce clear cut areas.

6. Increased Rotation Length

Increase in forest logging age in the European part of the FSU is theoretically realistic and would result in substantial additional sequestration of C. If the age of main cuttings were increased by 20 years on 20 percent of the forest areas presently

subjected to harvesting, an estimated 0.2 PgC/yr could be sequestered. However, high demand for wood by domestic and international users might prevent the implementation of this option.

Box 2: United States

The United States is a predominantly temperate zone country (Figure IV.1), occupying an area of 936 x 10^6 ha (765 x 10^6 ha in the conterminous U.S.). The total population is 263 x 10^6, and the population density is 280/1000 ha. Recent estimates of population project increases of nearly 1% per year over the next few decades, a rate that is low by comparison with many less developed countries but is considerably higher than many other industrialized, temperate-zone countries (WRI 1992). Per capita Gross National Product is relatively high at $21,000 per year and per capita energy consumption (2,956 GJ) is nearly the highest in the world (WRI 1992).

Land cover in the conterminous U.S. is approximately 1/3 forest, 1/3 rangeland, and 1/3 cropland, pastureland or other uses (USDA 1989). The proportion of the land base which is arable is relatively high (25%), and agricultural exports are a significant component of the national economy. The current ratio of potential forest land to actual forest land is 1.8 to 1 (Turner et al. 1993b), reflecting periods of extensive land-cover change over the last several centuries. Much of the remaining forest has been logged over the last century. After modest reversions of land from agricultural to forest use in the middle decades of this century, the rates of interconversions among the land-use categories have slowed (Alig et al. 1990; MacCleery 1992). A slow decline in the area of forest land is projected over the coming decades (4% by 2040) driven primarily by urbanization and conversion of forest land to agriculture.

Land ownership in the U.S. is predominantly private with the cropland, pastureland, and other categories almost exclusively found in private. Federal ownership of forest land and rangeland amounts to 33% of the total land in those categories (USDA 1989). Approximately 6% of the total forest land, primarily in public ownership, is reserved for conservation and recreational uses.

The forest products industry is important at the national scale and dominates the economy at the community level in some cases. Industrial forest lands, however, cover only 15% of the forest lands in the 50 states (Alig et al. 1990). Harvest levels have increased over the last few decades and now account for about 75% of net growth on forests land available for harvest (Powell et al. 1993). Public forest provide 18% of the national harvest (Powell et al. 1993).

The U.S. imports and exports logs as well as finished forest products. In the case of forest products, the value of imports were nearly double that of exports in 1985 (Haynes 1990). However by 1990, the value of imports had grown by 38% while that of exports grew by 133%, making exports equal to 84% of imports. For logs, the opposite was the case with virtually no imports but extensive exports. Exports were 8 times the imports in 1985 (by volume) and further increased to 11 times by 1990. At the national level, the net effect is an import of tree C.

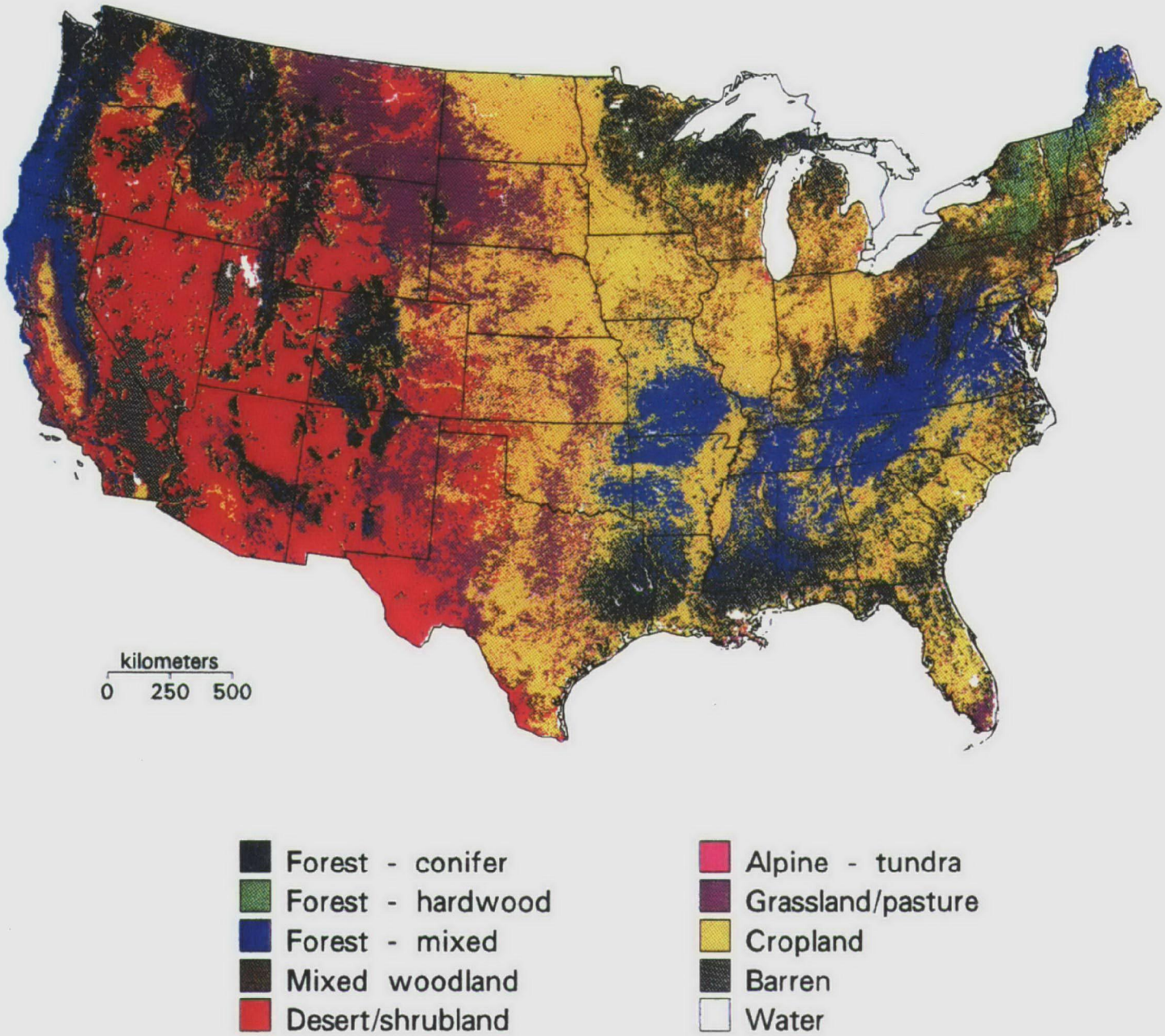


Figure IV.1. United States land-cover map derived from the AVHRR sensor (Loveland et al. 1991).

IV. United States Case Study

A. Introduction

The United States is a large, heavily industrialized nation and is characterized by relatively high per capita emissions of fossil CO_2. The country is also extensively forested. Reversion of land from agriculture and pastureland to forest in the mid decades of this century, and the recovery of lands in the eastern U.S. from earlier heavy cutting (USDA 1992a), has created a significant C sink (Heath and Birdsey 1993; Turner et al. in press a). The net C emissions of the U.S. thus reflect both sources associated with fossil fuel combustion and net sinks associated with the forest land base and forest products. In this section, previous studies and recent analyses are used to develop for the conterminous U.S. a C budget which accounts for both anthropogenic and biological factors.

The complete C budget includes C pools and principal C sources and sinks. Pools are subdivided into soil, litter, woody debris, and phytomass components. The C fluxes include those, such as fossil fuel emissions and accumulation of C in forest products and landfills, which are controlled primarily by anthropogenic factors, as well as those controlled by biological processes—notably net ecosystem production.

The C flux associated with the forest land base receives the greatest attention in the U.S. analysis. Recent studies suggest that the rate of conversion of land from one use to another is relatively low in the U.S. (Alig et al. 1990), so the C source from deforestation is minimal. However, much of the U.S. forestland is managed for timber production, and the relative rates of growth and harvest determine the direction and magnitude of the associated C flux. The harvest rates also influence the

rate of C sequestration in wood products still in use and in landfills.

B. Methods

The objective of this study was to estimate C pools and flux for the complete land base of the conterminous U.S. As an initial step, the land base was subdivided into the 5 land-use types used in the USDA Resource Protection Act reports (SCS 1987). The approach for estimating C pools and flux varied according to land-use category, and each will be discussed separately.

1. Forestland

In this category, all forested land capable of producing 1.4 m^3/ha/yr of industrial wood is treated. Lands available for harvest as well as reserved lands were included. "Other Forest" land or woodland (Powell et al. 1993), with relatively low total ecosystem carbon (TEC) and productivity, are treated below.

The basic approach to quantifying C pools and flux on forestland was to link a complete forest inventory for 1990 with a set of stand-level C budgets. The inventory contained information on the area and stocking level for each combination of region, forest type, age-class, productivity level, and management intensity. The stand-level C budgets contained estimates of C in the tree, understory, litter, woody debris, and soil (organic C) at each age class. The total C pool was quantified as the product of the areal extent, the stocking level of each age class (within each inventory type), and the C pool values in the associated stand-level C budget. The C flux was estimated by advancing the inventory one time step and considering harvest-related transfers.

a. The Forest Inventory

A forest inventory for private lands in 1990 was prepared as part of the USDA Forest Service 1993 Resources Planning Act Assessment (J. Mills, USDA Forest Service, Portland OR, pers. comm., 1994; Haynes 1990). The inventory reflects survey data from regional Forest Inventory and Analysis (FIA) work units (USDA 1992b) and was structured in the framework of the ATLAS inventory projection model (Mills and Kincaid 1992). The ATLAS-based inventory includes information on the area and stocking level within each age class for 422 combinations of region, forest type, productivity level, and timber management intensity. Uncertainty associated with FIA inventories is discussed in Peterson and Turner (1993).

Data for the age-class distributions on public lands within each forest type exist for particular areas, but they have not been compiled on a national scale. An estimate of the age-class distributions and stocking levels on public lands was developed, therefore, in part from data in recent state-level studies. These reports collated age-class data for national forests, reserved lands and other public lands in the Pacific Northwest region, where the largest volumes of public timber are found (MacLean et al. 1991; Sessions 1991; Adams et al. 1992). Other sources of data included the areas by forest type and the volumes by forest type on public lands reported in Waddell et al. (1989) and the age-class distributions on private lands (Turner et al. 1993a).

b. Construction of Stand-Level Carbon Budgets

The Forest Carbon Model (Turner et al. 1993a; Turner et al. 1994a, is a set of stand-level C budgets (e.g. Figure IV.2),

which relate the growth and yield tables from ATLAS to trends in total ecosystem C over the course of stand development. Allometric relationships are used for converting merchantable volume in the growth and yield tables into tree C. A modeling approach involving harvest residue, rates of tree mortality, and rates of dead wood decay is employed for estimating the pool of woody debris in each age class. Literature studies (Vogt et al. 1986) provide the basis for estimating the C in the forest floor and understory over the course of stand development. To arrive at representative soil C pools for each forest type, a map of soil C density (Kern 1994) was overlain with the spatial distribution of each forest type (Eyre 1980). Soil C was assumed to be stable over the course of stand development in accord with the recent literature (Alban and Perala 1992; Johnson 1992).

c. Estimation of Carbon Flux

The net C flux was considered to be the net accumulation or loss of C from the forestland base over a one-year period. The net flux thus includes C transfer between the forest and the atmosphere in either direction (i.e., growth, autotrophic respiration, and heterotrophic respiration) and C transfer out of the forest for human use. In an effort to isolate the effects of harvesting, we distinguished between biologically driven C flux and harvest-driven C flux.

d. Biologically-Driven Carbon Flux

The biologically driven C flux is an estimate of the net change in C storage expected over a one-year period assuming there had been no harvest. The physiological processes involved are primarily photosynthesis and autotrophic plus heterotrophic respiration. This flux for individual forest components and the total flux, which reflects net changes in all the pools (i.e.,

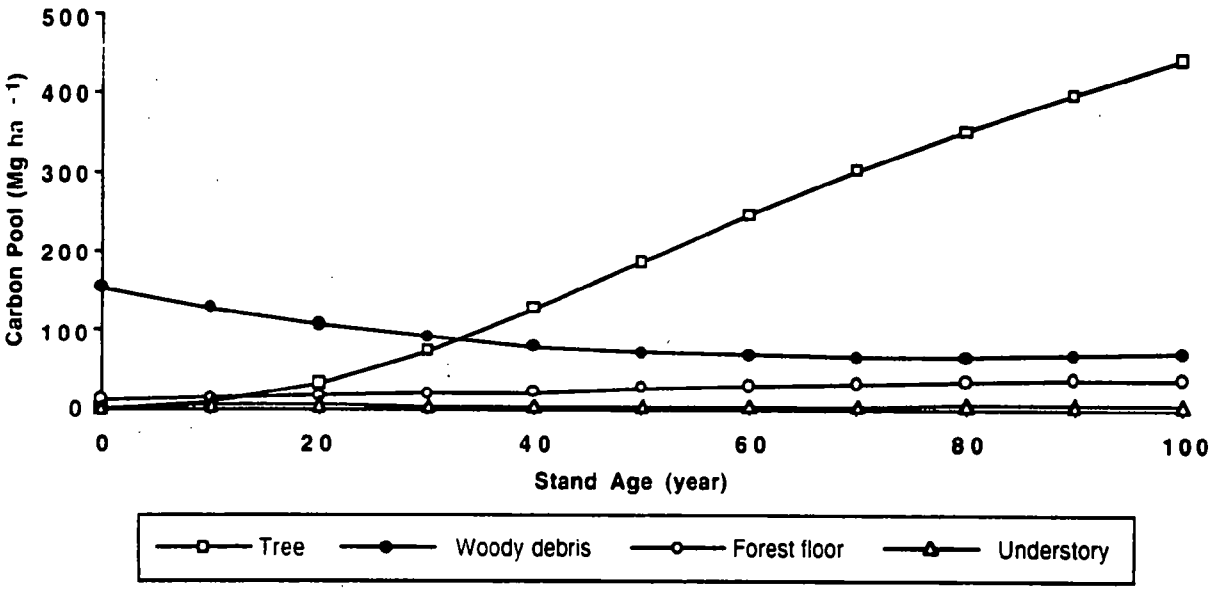


Figure IV.2. Pacific Northwest Region sytandard carbon budget for medium productivity of Douglas-fir (Turner et al. 1994a).

net ecosystem production), were based on the inventories and stand-level C budgets described earlier. Using the ATLAS model for private lands and a spreadsheet approach for public lands, the entire inventory was advanced one time step (5 years in the southern regions, 10 years elsewhere) and flux was based on annualized changes in pools over the time increment.

In order to derive an estimate of annual forest NPP, information on wood growth was combined with literature data on rates of leaf (fine litterfall) and fine root production. To obtain a ratio of wood production to foliage production, data on these two variables was extracted from 68 relevant studies in Cannell (1982). The studies covered a range of stand ages and included thirty-one coniferous stands and thirty-seven deciduous stands. Average aboveground wood production from these studies (6.7 Mg/ha/yr) was multiplied by 1.15 to approximate inclusion of coarse root production (Koch 1989). The average ratio of wood production to foliage production was then 2.3 ± 1.4. Average fine root production was estimated from average foliage production using the regression of Nadelhoffer and Raich (1992), which was developed from 59 studies in the literature wherein aboveground fine litter production and fine root production were measured. Thus the average foliage production of 3.5 ± 0.9 Mg/ha/yr was estimated to be associated with a fine root production of 2.7 Mg/ha/yr. The final ratio of total production to wood production was 2.0.

e. Harvest-Driven Carbon Flux

The volume of harvest removals or growing stock reduction for the 1990s for private lands was that used in the 1993 Resource Planning Act (RPA) Assessment, and the distribution of the harvest among regions and forest types was derived from the ATLAS

model. The distribution of the removals among regions and ownerships is similar to that reported in Powell et al. (1993).

Estimates of growing stock from public lands were projections for the 1990s from the 1989 RPA Assessment. A harvest of 87 x 10^6 m^3/yr was assumed here, which is higher than the estimate of 81 x 10^6 m^3/yr for 1992 in Powell et al. (1993) but probably close to what the decade average will be since harvest levels are projected to increase. In order to estimate the area harvested on public lands, the harvest volume within a region was distributed across forest types and age classes by generally assuming an equivalence in the distribution of harvest across forest types and age classes between public and private lands within a region. In the forests of the Pacific Northwest region, data were used from Sessions (1991) on the distribution of the harvest among age-classes on public lands.

The tree C on harvested lands which was not accounted for as growing stock removals or formation of woody debris residue (calculated as the difference in the stand level C budgets between post-harvest and pre-harvest woody debris on all harvested areas) was assumed to be emitted within the year of harvest. This residual could be considered to include slash burns and perhaps additional material which might be removed from the site but returned to the atmosphere relatively quickly (e.g. fuelwood). The understory and part of the litter layer of harvested stands were also assumed to be either burned or rapidly decomposed, and this loss was likewise treated as instantaneous.

The harvest in ATLAS included some lands which are cut but not returned to the timberland base. In the 1993 RPA Assessment projection, the average rate of reduction in the forestland base in the 1990s was 201 x 10^3 ha/yr (Alig et al. 1990). All carbon in woody debris on these lands was assumed to return to the

atmosphere. This source of C was termed the "land conversion flux."

f. Fire Emissions

A separate estimate of forest wildfire emissions is not in principle necessary for this C budget. Mortality derived from noncatastrophic wildfire is a component of the woody debris budgets (Turner et al. 1993a). Catastrophic wildfires are somewhat analogous to harvests when they are salvage logged which is often the case. To the degree that this growing stock contributes to the harvest targets and direct fire emissions mimic slash emissions, these C fluxes are captured in our budget.

Direct wildfire C emissions appear to be on the order of 20 Tg/yr (approximately 10^6 ha), using a long term average (A. Auclair, Science and Policy Associates, Washington D.C., pers. comm., 1994). Approximately one-third of the wildfire emissions are associated with woodlands, which tend to maintain a long-term C equilibrium on those lands. Prescribed fire, including slash burns, may generate an additional 10-20 TgC (Yamate 1974), however, this flux is also captured in the modeling of the harvest-driven C flux. Because fire was not treated explicitly, formation of charcoal has not been considered in this analysis.

2. Woodlands

Woodland is defined as forested land with potential growing stock accumulation rates of less than 1.4 m^3/ha/yr (Waddell et al. 1989) e.g., the juniper (*Juniperous occidentalis*) woodlands of eastern Oregon. For woodland phytomass, an average value of 13.0 Mg/ha from the compilation of Peterson (1993) was used. Woodland NPP was based on an estimated average wood production of 0.7 m^3/ha/yr (half the maximum accumulation rate), and the same ratio

of total production to wood production was used here as on forestland. Woodland NEP was assumed to be zero because climatic factors and wildfire tend to keep TEC accumulation low. There was no database from which to estimate woodland soil C density. As a preliminary estimate, a value midway between the average for forestland and rangeland soil C was assigned to woodland.

3. Rangeland, Pastureland, Cropland, and Other Land

For non-wooded land, litter and woody debris pools were assumed to be zero. The C pool for vegetation phytomass was assumed to be the same as the NPP. The effect of that assumption is to place an upper bound on the phytomass pool rather than an annual average. The annual NPP was assumed to be balanced by annual decomposition (i.e. NEP equal to zero) or fire. The average soil C pool for nonforested land is based on soil C, by great group, determined from the SCS National Soil Survey Laboratory Pedon Database as calculated by Kern (1994), adjusted for soil depth and rock fragment for the subsoil by data from the SCS Soil-5 database and rock fragment content for the surface horizon based on the texture modifier from the 1982 National Resources Inventory (NRI).

Net primary productivity for non-forested lands was estimated using land-cover data from the 1982 NRI database (SCS 1987) and several different NPP databases (King 1993b). Estimates of rangeland aboveground net primary production (ANPP) were obtained from the Soils-5 interpretation records (SCS 1983). Rangeland ANPP was converted to NPP by reference to ANPP/NPP ratios (~3:1) derived from field studies in the literature. Pastureland NPP for each state was estimated by assuming a NPP equivalent to the average hayland total NPP for the same state. Cropland NPP was obtained by converting crop yield data (SCS 1987) to estimates of

total plant yield. "Other Land" NPP was assumed equal to the average NPP of the other three general cover types.

C. Results

The total land of the conterminous U.S. is 765.6 X 10^6 ha, of which 200.7 X 10^6 ha is timberland (Table IV.1). A check of forest area derived from this inventory (243 X 10^6 ha) with forest cover derived from a recent land-cover map based on satellite remote sensing (252 X 10^6 ha) indicated reasonable agreement (within 4%) at the national level (Turner et al. 1993b). At the state and regional levels, greater differences were apparent. The area of rangeland is comparable to the sum of forestland and woodland. Cropland and pastureland cover 154.7 and 54 X 10^6 ha respectively.

The average nonsoil (phytomass + CWD + litter) C density in forestland (93.3 Mg/ha) is an order of magnitude greater than that in the other land-cover types (2.3—13.0 Mg/ha, Table IV.1). Forestland dominates the total in the phytomass C pool (Table IV.2). Considering all C pools (87 Pg), the soil C component is largest at 75% with phytomass C accounting for much of the remainder.

Average NPP density is highest in cropland (Table IV.3), reflecting subsidies of nutrients and protection from pests and pathogens. Cropland also has the highest total NPP among the vegetation types. Only forestland is considered to sequester C on an annual basis in this analysis, and forest sequestration (including phytomass, CWD, and litter) amounted to 95 Tg/yr (Table IV.4).

Detailed results by land-cover type are given below.

Table IV.1. Area and Carbon Density by Land-Use Category, United States

Ecosystem/ Land Use	Area (Mha)	C Density (MgC/ha)			
		Phytomass	Litter	Woody debris	Soil
Forestland	200.7	63.1	11.6	18.6	91.1
Woodland*	41.2	13.0	NA	NA	78.6
Pastureland†	54.0	4.3	NA	NA	87.6
Rangeland†	246.8	2.3	NA	NA	66.2
Cropland†	154.7	5.3	NA	NA	105.2
Other†	68.2	2.5	NA	NA	86.3
Total	765.6				

*Peterson 1993.

†King 1993a.

NA Not Applicable.

Table IV.2. Total Carbon Pools for the Conterminous United States

Ecosystem/ Land Use	C Pool (TgC)				
	Phytomass	Litter	Woody debris	Soil	Total
Forestland	12,663	2,324	3,730	18,280	36,997
Woodland*	1,550	NA	NA	3,238	4,788
Pastureland†	230	NA	NA	4,730	4,960
Rangeland†	578	NA	NA	16,338	16,916
Cropland†	815	NA	NA	16,274	17,089
Other†	171	NA	NA	5,886	6,057
Total	16,007	2,324	3,730	64,746	86,807

*Peterson 1993.

†King 1993b.

NA Not Applicable.

Table IV.3. Total Net Primary Production for the United States

Ecosystem/Land Use	Average (MgC/ha/yr)	Total (Tg/yr)
Forestland	3.46	695
Woodland	1.05	43
Pastureland	4.26	230
Rangeland	2.34	578
Cropland	5.29	815
Other	2.51	171
Total	NA	2,532

NA Not applicable.

Table IV.4. Carbon Balance on the Forestland Base, United States

Factors	Carbon (TgC/yr)				
	Tree	Woody Debris	Litter	Understory	Net
Biological*	359	-66	32	7	332
Harvest*	-275†	73	-28	-7	-237
Combined	84	7	4	0	95

*Biological and harvest refer to the net change in pool size as a function of biologically-related or harvest-related factors.

†Includes growing stock removals (-125), woody debris formation (-73) and harvest emissions (-77).

1. Forestland

a. Carbon Pools

Half of the total forestland C is in the mineral soil (Table IV.2). Phytomass C, which includes coarse roots and understory, is the next largest component at 33%, followed by woody debris (10%), litter (6%), and understory (1%). The total C storage in living trees on forestland in the U.S. is estimated at 12.2 Pg (Table IV.2). The average storage for total phytomass C was 63.1 Mg/ha (Table IV.1). While direct comparisons are difficult, the tree C pools appear to be consistent with earlier analyses based on USDA FIA statistics (Cost et al. 1990, Birdsey 1992).

b. Biologically-Driven Flux

The estimated NPP for forestland was 695 TgC/yr (Table IV.3) based on wood production derived from the inventory advancement procedure and the ratios of fine root and leaf production to wood production. The net flux of C into the forest from tree growth (after accounting for mortality and turnover of foliage and fine roots) was 359 TgC/yr (Table IV.4). Carbon also accumulated in the understory (7 TgC/yr) and forest floor (32 TgC/yr) pools. The only pool to show a net C emission (66 TgC/yr) was the woody debris pool. This efflux was driven by the decay of woody debris in the early to middle stages of stand development. During these periods, the quantity of C emitted from woody debris created at the time of stand origin (due to harvest, wildfire, etc.) and from woody debris remnant from the previous stand far exceeds carbon inputs to the compartment originating in tree mortality (Harmon 1993). The overall net flux of C driven by biological processes was 332 TgC/yr moving from the atmosphere into forest stands.

Limited opportunities exist to validate these biological flux estimates. Powell et al. (1993) estimated timber volume growth on U.S. available timberland at 598 X 10^6 m^3 for 1991 based on repeated sampling of permanent plots. The comparable value in the present analysis is 590 X 10^6 m^3. The tree growth estimate here (359 TgC/yr) compares closely with the estimate in Birdsey (1992).

c. Harvest-Driven Carbon Flux

The effect of timber harvest is manifested in several ways (Table IV.4). Most significant is the transfer of a large quantity of C out of the tree phytomass pool (275 Tg). In the U.S., this reduction in tree C is about 80% of the annual C accumulation from tree growth.

Of the 275 Tg total reduction in the phytomass C pool, 125 Tg was associated with harvest and removal of the growing stock. The remainder of the tree C on the harvested land (-150 Tg) was partitioned between the harvest emissions (-77 Tg) and a transfer to the woody debris pool (+73 Tg). Partitioning of the harvest residue between formation of woody debris (49%) and short term emissions (51%) is consistent with the observation that roots and stumps generally remain after harvest.

The rapid change in forest floor and understory C associated with or immediately following harvesting amounted to a 35 Tg/yr loss of C, which brought the harvest emissions total to 112 TgC/yr when combined with the 77 Tg of tree carbon (Table IV.4).

d. Complete Forestland Flux Analysis

The net effect of forest growth and decomposition was a transfer of 332 TgC/yr from the atmosphere into organic matter. This rate

of potential accumulation is possible only because the removal of C by harvesting has tended to maintain a large area in the early to mid-stages of stand development which favor C accumulation. Under unmanaged conditions, the rate of C accumulation on the same land base would be lower or even negative because fire and increased rates of woody debris decomposition would balance uptake. The potential accumulation of 332 TgC/yr was partially offset by harvest-related removals from the forestland base totaling 125 TgC/yr (Table IV.4) and harvest emissions of 112 TgC/yr (Table IV.4). The difference between the biological flux and the losses associated with harvest is a gain of 95 TgC/yr on the forestland base. A loss of 4 TgC/yr of woody debris C was estimated for lands which were harvested but not returned to the forest land base.

The live tree C pool is increasing because tree growth is greater than the C in mortality and trees harvested. The simplicity of the assumptions about woody debris dynamics lends a high degree of uncertainty to the net flux estimate for woody debris (7 TgC/yr). Over the last several decades utilization of harvest residues has tended to increase, and the inventory of older forests carrying large quantities of woody debris has decreased. At the same time, the average age-class of stands in the U.S. has probably fallen because of increasing harvesting and management. Younger stands carry more woody debris in the form of stumps and harvest residues. These counteracting factors make it difficult to assess the overall change in the storage of woody debris. More recently, forest management regulations have begun to require that some woody debris be left on-site for wildlife habitat (Swanson and Franklin 1992), and that trend will also favor woody debris accumulation.

The results here for net accumulation of tree C may be compared with other recent national analyses. Heath and Birdsey (1993) used current inventory data and inventory projections to estimate

accumulation of live and dead C for timberland in the conterminous U.S. The live C accumulation for the period 1987-2010 was 17 TgC/yr. That value does not include reserved timberland (11.7 X 10^6 ha), which is estimated here to sequester about 10 Tg/yr, and does reflect the general trend of a decreasing tree C sink on the forest land base over the coming decades (Turner et al. 1994b). Our estimate of tree C gain for the 1990s (84 Tg/yr) is roughly consistent with the growing stock accumulation for 1991 reported in Powell et al. (1993). They indicated an annual accumulation (net growth - removals) on available timberland in the conterminous U.S. of about 140 x 10^6 m^3 of growing stock which represents about 34 Tg of growing stock or about 70 Tg of whole tree C. Subak et al. (1993) similarly estimated the 1990 C accumulation on the commercial forestland base at 60 TgC/yr based on inventory statistics from the Food and Agriculture Organization of the United Nations.

2. Woodland

Woodland represents 5.4% of the total area of the conterminous U.S. but woodland NPP is only 1.7% of total NPP (Table IV.3). Wood production within woodlands is about one-third of NPP, so it amounts to 15 Tg. Our earlier estimate of emissions from woodland wildfire was approximately 7 TgC/yr, thus the remainder (8 TgC/yr) is assumed to be balanced by decomposition such that NEP for woodland as a whole is zero.

3. Grassland, Rangeland, Pastureland, Cropland and Other Land

Non-forested land constitutes about 70% of the land surface of the conterminous United States. Rangeland is the dominant non-forest cover type, accounting for about half of the non-forested land. Cropland is the most productive cover type, with a mean

NPP of 5.3 MgC/ha/yr, while rangeland is the least productive, with a mean NPP of 2.3 MgC/ha/yr (Table IV.3). Overall, NPP for non-forested land in the U.S. is estimated to vary by about 20% between favorable and unfavorable years, or about 0.7 PgC (King 1993b).

Normal tillage practices in croplands of temperate zones tend to decrease soil C until a stable equilibrium is reached. Much of the agricultural land in the U.S. has reached this equilibrium but a small C source (1.5-2.6 Tg/yr) is still indicated (Kern and Johnson 1991).

D. Discussion

NPP is by far the largest C flux among the processes evaluated in this analysis. At 2,532 Tg/yr (Table IV.3), C uptake via NPP is nearly twice C release via fossil fuel emissions (Table IV.5). However, uncertainty about the magnitude of NPP is large and the great majority of NPP is returned to the atmosphere relatively rapidly. Only 95 Tg/yr of NPP accumulates on the forestland base. Another 36 Tg/yr accumulates in forest products still in use (Birdsey et al 1993; Turner et al 1993a), and 10 Tg/yr in landfills (Subak et al. 1993). C emissions from land conversion and agricultural tillage (Table IV.5) are relatively small and are to some degree counteracted by factors untreated here such as urban forestation (Rowntree and Nowak 1991). Thus, in terms of net flux, fossil fuel emissions are an order of magnitude larger than the biologically based net C sinks. The accumulation of C on the forestland base of the U.S. is similar to trends in many northern temperate zone countries (Clawson 1979; Armentano and Ralston 1980; Sedjo 1992; Kolchugina and Vinson 1993d; Kauppi et al. 1992; Birdsey et al. 1993). Recovery from earlier periods of extensive forest harvest and limited management is now resulting in C accumulation. Specific factors in the U.S. include

Table IV.5. Net Carbon Flux for the Conterminous United States*

Source	Carbon (TgC/yr)
Energy	-1,296†
Cement Manufacture	-10†
Forest Sector	
Forest Land Base	95
Forest Products	36‡
Conversion Emissions	-4
Agricultural Sector	
Agricultural Land Base	-2§
Landfills	10†
Net	-1,171

*Emission of CO, methane, and other hydrocarbons are excluded. Negative values are carbon transfers to the atmosphere.

†Subak et al. 1993.

‡Birdsey et al. 1993.

§Kern and Johnson 1991.

reversion of agricultural land to forest (Williams 1988) and fire suppression (USDA 1992a). The combined effects of these factors in northern temperate zone forests is believed to be an accumulation of 700 Tg/yr (Sedjo 1992). A terrestrial sink of this magnitude is needed to balance the global C budget (Post et al. 1990; Siegenthaler and Sarmiento 1993).

Several studies have examined the possibility of significantly increasing the sink on the forestland base. Suggestions have included increased paper recycling, reduction in the harvest on public land, and afforestation (Turner et al. 1993a, Turner et al. 1994b; Winnett et al. 1993). An increase in paper recycling to 48% by the year 2000 was estimated to increase sequestration on the forestland base by about 5 Tg/yr over a 50 year scenario (Turner et al. 1993a). The harvest reduction scenario in Turner et al. (1993a) called for a 20% reduction in the harvest on national forestland (3.4% of the total U.S. harvest). Isolating the public land base, the effect of the harvest reduction was an additional C sink on the order of several Tg/yr. The harvest on private land could potentially rise in response and negate the sink; however, the forest economic model used in these scenarios did not indicate such a response in this case (Figure IV.2). Likelihood confounding factors include potential changes in imports and exports of logs and forest products.

The potential for C sequestration from afforestation of marginal pasturelands and croplands is much larger (Moulton and Richards 1990; Sampson and Hair 1992; Barker et al. [submitted]). As much as 47 X 10^6 ha of such land could be converted to forest (Parks et al. 1992), and the C sink associated with a land conversion of this magnitude would sequester a significant fraction of U.S. fossil fuel emissions. The costs of establishing the forests and the long-term land rents are substantial, on the order of billions of dollars per year. A scenario in which $220 million per year for 10 years was invested in afforestation (5 X 10^6 ha)

according to the scheme of Moulton and Richards (1990) resulted in an average C sink of 15 Tg/yr over a 50 year scenario (Turner et al. 1993a). Land rent costs beyond the initial 10 years were not accounted for, and these might raise costs significantly.

Box 3: Mexico

Mexico straddles the tropic of Cancer, extending from 33°N to 14°N latitude. This nation of approximately 196 X 10^6 ha comprises 31 states and the Federal District of Mexico, the capital. The 1990 population of Mexico was 88.6 million people (the largest Spanish speaking country in the world), corresponding to a population density of 452 people/1000 ha (WRI 1993). However, greater than 70% of this population lives in urban areas, with Mexico City considered to be the largest city in the world (1990 population approximately 20 million people). The population growth rate of Mexico, 2.2%/yr between 1985 and 1990 (WRI 1993), is similar to that of Brazil.

Highly organized indigenous civilizations in Mexico today date back at least to 1200 B.C. with the rise of the Olmec civilization in eastern Mexico. Spain began the European conquest of Mexico in 1519, and today the Spanish language is the predominant language in most regions of the country. Indigenous populations exist throughout the country, though the Mayan populations in southern Mexico are perhaps the largest. The Mayans are only partially assimilated into the dominant Latin culture.

Mexico is a rapidly industrializing country. In Latin America, Mexico is second only to Brazil in population and GNP, yet it exceeds Brazil in commercial energy production and estimated C emissions from industrial sources (WRI 1993). At the same time, FAO (1993) estimates that Mexico had the second highest amount of deforestation in Latin America during the 1980's, though for the humid tropical forest type it is less than one fifth of that deforested in Brazil during the same time period.

A broad diversity of tropical and temperate ecosystems exists in Mexico (Figure V.1) due to its position at the junction of the neotropical and holarctic zones, and its extensive vertical relief. Drylands and temperate forests of coniferous and broadleaf trees in the northern highlands grade into tropical deciduous and evergreen ecosystems in the southern lowland areas. Mangrove forests and wetlands exist along both the Atlantic and Pacific coasts.

Once extensively forested, many Mexican forests, especially the tropical forests, have been converted to pastoral and agricultural land uses. Rzedowski (1978) estimated that the current extent of tropical evergreen forests represents approximately 10% of the extent of these forests prior to human-induced land conversion. In some areas, deforestation occurs within the context of various traditional systems of shifting agriculture involving forest-fallow (Ita-Martinez et al., Universidad Nacional Autonoma de Mexico, unpublished manuscript; Bellon 1991). In other areas, government land tenure or agricultural subsidy policies have influenced forestland conversion (Ramos and del Amo 1992; Williams-Linera 1983). Recent land tenure reforms were enacted to slow forest conversion and to promote sustainable use and restoration of Mexican forest resources (Masera et al. 1995.

The wood products industry of Mexico is small relative to the national economy, and Mexico is not self-sufficient in terms of meeting national wood products demand (CNIF 1992). Although roundwood production has historically exceeded demand, production fell short of consumption by 10% in 1991. Mexican production of wood fiber products meets less than 50% of its national demand (CNIF 1992).

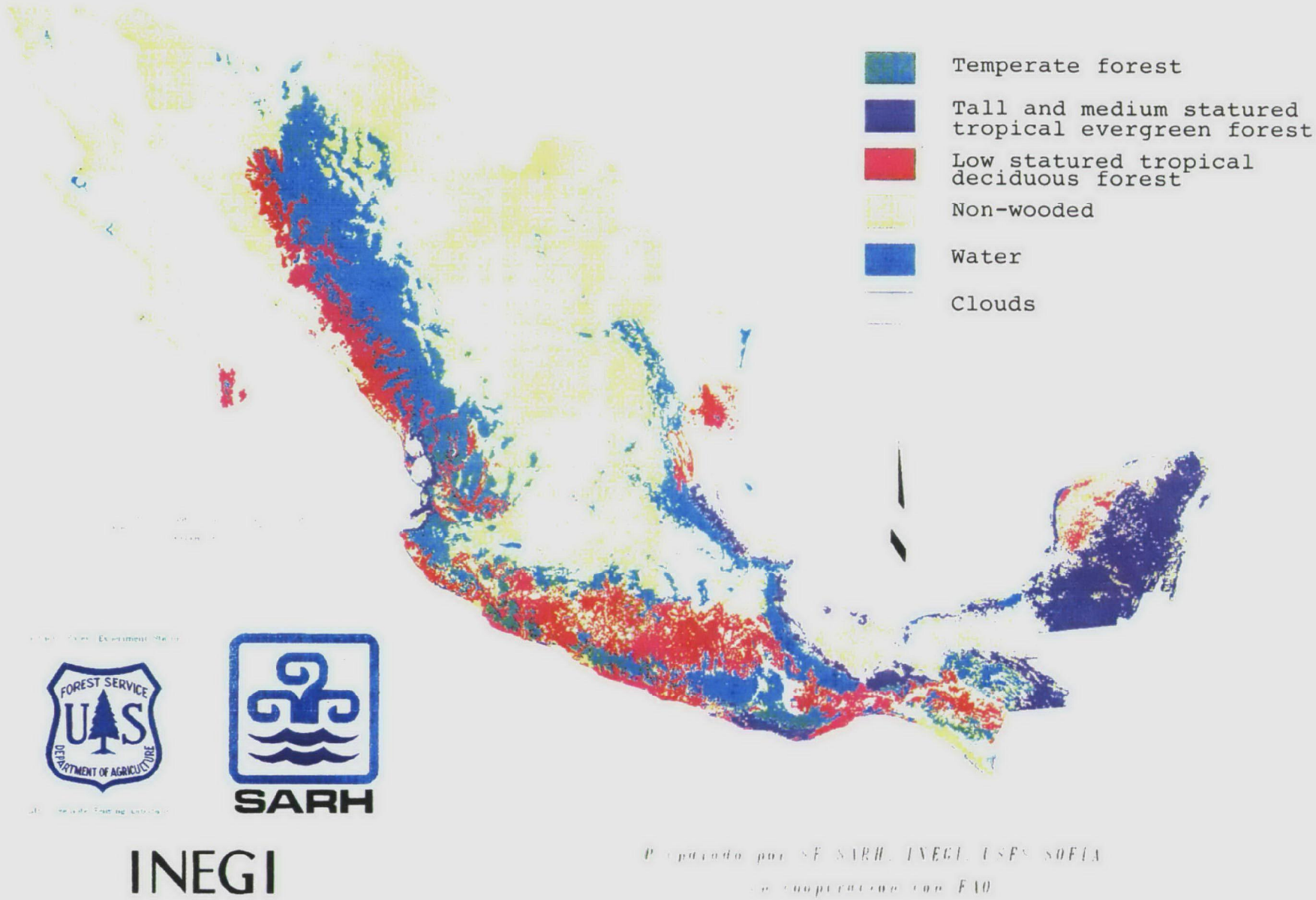


Figure V.1. Forest map of Mexico produced by classification of composite 1990 and 1991 AVHRR images.

V. Mexico Case Study

A. Introduction

A C budget for Mexico, as for other nations, requires information on four broad elements: (1) an estimate of land cover; (2) transition rates between land-cover classes (e.g., forest conversion to pastureland); (3) carbon density estimates of each land-cover component; and (4) estimates of the effects of land-use changes on C pools. Published C budgets for Mexico, focusing on forest ecosystems, have brought together much of the published and unpublished data collected in Mexican forest ecosystems (Masera et al. 1992). Though a slightly different approach is used, this section draws upon that study and other sources of data to model forest C. This section extends C budget analysis to all land-cover types and incorporates recently available land-use and vegetation information.

B. Methods

The types of land use in Mexico can be divided into six broad categories (Table V.1). Approximately 36% of Mexico is classified as forestland. This category is composed of both fully-stocked forests (greater than 5 m in height, crown cover not specified) and what Secretaría de Agricultura y Recursos Hidráulicos labeled perturbed forests (SARH 1992), though the interpretation of this category is uncertain. The fully-stocked forest category includes both temperate and tropical forests. Temperate forests include coniferous (9% of total area of Mexico) and broadleaf forests (4%). Tropical forests include humid tropical (5%), dry tropical (7%) and mangrove forests (< 1%). Perturbed forests (11% of total area) are not distinguished by vegetation type (SARH 1992; Table V.2).

Table V.1. Areas of Major Land-Cover Types in Mexico*

Land-Cover Type	Area	
	X 10^6 ha	%
Forest†	71.28	36
Woodland/scrub†	66.42	34
Pastureland‡	38.37	20
Cropland‡	13.14	7
Wetland†	1.20	1
Mangrove forest†	0.53	<1
Other†	4.88	2
Total†	195.82	100

* Based on SARH (1992) which is the most recent and comprehensive survey of land use in Mexico to date.

† Developed from multidate composites of NOAA-11 satellite AVHRR data and ancillary maps (Evans et al. 1992). Uncertainty levels for 11 of estimates area are unknown.

‡ Masera et al. (1992) provide estimates of the proportion of non-forest lands in cropland and pastureland based in part on data from SARH (1992). These proportions were used in this section to estimate the area of cropland (13.14 X 10^6 ha) and pastureland (38.37 X 10^6 ha) for the purpose of modeling standing stock of C.

After forests, the next largest land area is composed of woodland/scrub (34% of total area of Mexico) (Table V.1). This class includes matorral or scrub (28%), chaparral (4%), mesquite (1%), and miscellaneous shrubland covers. Other land-cover classes include agricultural/pastoral (27%), wetlands (1%), desert (1%), water (1%), and urban (< 1%). The agricultural/pastoral land use class was not distinguished according to previous land cover (SARH 1992). In this section, the agricultural/pastoral land-cover class was divided into cropland and pastoral classes according to percentage estimates used by Masera et al. (1992). Thus, cropland is estimated to represent 7% of the total land cover of Mexico and pastureland 20% (Table V.1).

Estimates of the area, TEC, and rate of conversion of each land-use type were entered into a spreadsheet model. Carbon fluxes from past land-use changes (i.e., regrowth and continuing decomposition of slash and soil organic matter on sites converted from forest within the past 10 years) are incorporated as "inherited emissions" (i.e., C released to the atmosphere predominantly due to phytomass burning and, to a small degree, from decomposition of wood products or soil C). These were added to base year, "prompt emissions" to calculate total C emissions. This follows the convention of Makundi et al. (1992). The standing C stocks and fluxes were estimated for a nominal base year of 1990.

1. Land Cover

Land-cover change is extremely dynamic in some regions of Mexico (e.g., 7.7% annual deforestation rate from 1974-1986 in Chiapas; Cuarón 1991). The first Mexican National Forest Inventory (SARH 1986), completed in 1985 after a 24 year study, was largely out of date by the time it became available. Masera et al. (1992)

Table V.2. Estimates of Land Cover and Annual Deforestation Rates in Mexico

Land-Cover Type	Total Area ($X\ 10^6$ ha)		Annual Deforestation ($X\ 10^6$ ha)
	SARH (1992)*	Masera et al. (1992)†	Masera et al. (1992)†
Temperate conifer forest	17.0	16.9	0.108
Temperate broadleaf forest	8.6	8.8	0.059
Humid tropical forest	10.5	9.7	0.195
Dry tropical forest	13.7	16.1	0.306
Total closed forest	49.8	51.5	0.668
Open forest	ND	31.1	NA§
Woodland/scrub‡	66.4	ND	ND
Perturbed forest	21.6¶	ND	ND
Other forest (mangrove)	0.5	ND	ND
Total other forest	88.5	31.1	NA
Pastureland	38.4#	79.9#	ND
Cropland	13.1#	27.4#	ND
Wetland	1.2	ND	ND
Total non-forest	52.7#	107.3#	ND
Other	4.9	6.7	ND
Total Land Area	195.8	196.6	0.668*

Table V.2 (Continued)

*Land cover estimates were derived from analysis of AVHRR imagery and existing national forest inventory information.

†Land cover estimates were derived from various data sources reported by Masera et al. (1992) including earlier SARH estimates.

‡This class includes matorral (55.5 X 10^6 ha), mesquite (2.8 X 10^6 ha) chaparral (7.7 X 10^6 ha), and miscellaneous shrublands (0.4 X 10^6 ha).

§Not available. Masera et al. (1992) declined to include open forests in their C analyses due to a lack of data on deforestation for this class and the low C density associated with its vegetation.

¶SARH (1992) includes moderately perturbed (18.1 X 10^6 ha) and severely perturbed forests (3.5 X 10^6 ha) in this category.

#Masera et al. (1992) provide estimates of the proportion of non-forest lands in cropland and pastureland based in part on data from SARH (1992). These proportions were used in this section to estimate the area of cropland (~13 X 10^6 ha) and pastureland (~38 X 10^6 ha) (Table V.1) for the purpose of modeling standing stocks of C.

♠Area-weighted mean of deforestation rates for all forest zones of closed forests as defined by Masera et al. (1992).

NA No data available.

ND No datum.

drew upon these and other data to estimate 51.5 X 10^6 ha of closed forest and 31.1 X 10^6 ha of open forest (Table V.2).

A national forest inventory was recently completed (Sorani et al. 1993). The preliminary estimates of land cover used to stratify the current Periodic National Forest Inventory include land area under non-forest land uses (SARH 1992; Evans et al. 1992). This analysis is based on interpretation of 1-km AVHRR imagery from 1990-1991 combined with existing forest inventory data. Estimates of closed forest cover by SARH (1992) differ only slightly from those used by Masera et al. (1992) (Table V.2).

The land-cover estimates of Masera et al. (1992) and SARH (1992) diverge, however, in estimating the proportion of land dedicated to open forest, pastureland, and cropland. Masera et al. (1992) use an estimate of pastureland and cropland area (107.3 X 10^6 ha) which is double that used by SARH (1992) (51.5 X 10^6 ha) with a consequently smaller area labelled as open forest (Table V.2). The difference is due in part, to differences in the definition of forest cover. Many areas used for pastureland in Mexico hold significant phytomass in woody vegetation and trees either as isolated individuals or as live fencing (Guevera et al. 1992). Some of these areas may be included in the SARH (1992) estimate of woodland/scrub forest or of perturbed forest. This section uses the area estimates of SARH (1992) since that data is based on the most recent and most comprehensive survey of land use in Mexico to date. The differences in area estimates of the woodland/scrub and forest categories, however, will have an effect on estimates of C pools and on C flux. A significant portion of the perturbed forest area estimated by SARH (1992) may have potential for sequestering C through forest growth even if these lands are not highly productive.

Masera et al. (1992) further provide estimates of the proportions of deforested areas which are converted to pastureland or

cropland (i.e., 79.9 X 10^6 and 27.4 X 10^6 ha; Table V.2). These same proportions (75% and 25%) are used in this section to estimate the proportion of pastureland or cropland converted from the humid and dry tropical forest types during the last 10 years (i.e., 0.195 and 0.306 X 10^6 ha/yr, respectively, from Table V.2). Therefore, this section estimates that 3.9 X 10^6 ha of forestland has been converted to pastureland and 1.1 X 10^6 ha has been converted to cropland during the past 10 years.

The main elements contributing to the net flux of C in the woodland/scrub category are vegetative growth which fixes C, and phytomass removals by pastoral and woodcutting activities which cause C losses. Since definitive data are not available for these processes, this section considers the woodland/scrub category to be in approximate C equilibrium, with vegetation growth balanced by pastoral and woodcutting phytomass removals.

For perturbed forests, Eggen-McIntosh (USDA Forest Service, pers. comm., 1994), interprets this SARH (1992) category as being fragmented forest roughly equivalent to the 10-40% forest cover class of FAO (1993). Much of this land is continually perturbed through repeated cultivation. Masera et al. (1995) also considered the perturbed forest category to include many areas that have long sustained shifting cultivation. They state that forest productivity on these lands is low and that forest plantations are generally not commercially viable.

For this section, there was insufficient information to make a definitive estimate of the C dynamics of perturbed forest systems; therefore, two possible scenarios were evaluated. In the first scenario, only the area equivalent to those lands that had been recently (during the last 10 years) deforested through timber harvesting or wildfires (about 13.5%; SARH 1992) are modeled as having net C sequestration. In the alternative scenario, fully 50% of the moderately disturbed category (SARH

1992) is modeled with a low net C sequestration; the other 50% is presumed to be in rough C equilibrium as continuing human perturbations balance C sequestration. These scenarios are extremely tenuous; from the viewpoint of C sequestration they are likely conservative since fragmented forests are widespread throughout this land-cover type. The assumptions underlying these scenarios, however, dramatically affect the final emissions estimate for Mexico.

2. Carbon Density Estimates

There are few published TEC data for Mexican ecosystems. Masera et al. (1992) used phytomass estimates generated from five case studies, one of which involved the direct measurement of forest phytomass. Direct measurements of forest TEC pools have been published for only a few sites in Mexico (Williams-Linera 1983; Wadsworth et al. 1988; Castellanos et al. 1991; Martinez-Yrizar et al. 1992).

For this section, estimates of Olson et al. (1983, 1985) were used for vegetation C content (Table V.3) because these are some of the only published estimates commonly in use for all Mexican vegetation types present in Mexico. It is recognized that these estimates are based on a global database and may be high for Mexico (J.S. Olson, Global Patterns Company, Lenoir City, TN, pers. comm., 1993). To account for this, the low estimates published in Olson et al. (1983) or the revised values in Olson et al. (1985) were used in this section (Table V.3). Olson phytomass values were converted to above- and belowground phytomass pools according to published conversion factors using root/shoot ratios (Table V.4).

Table V.3. Phytomass Carbon Density (above- and belowground) in Mexico by Land-Cover Type

Land-Cover Type	Phytomass (MgC/ha)		
	Olson et al.* (1983, 1985)	Masera et al. (1992)	Others
Tropical humid forest	150	144	139-265[†]
Tropical dry forest	50	67.5[§]	60[‡] 52[¶]
Temperate coniferous forest	60	56	ND
Temperate broadleaf forest	50	39	ND
Wetland	1.5	ND	ND
Mangrove forest	30	ND	ND
Grassland/shrub	20	ND	ND
Desert	2	ND	ND
Cropland	6	ND	ND
Pastureland	5	ND	ND
Perturbed forest	40	ND	ND

*This Section uses data of Olson (1983, 1985) for C density estimates.

†Mean value of four plots calculated from data provided by M. Ricker and M. Quinlan (Yale, 1993, personal communication) using the phytomass equations of Brown et al. (1989) and a root/shoot ratio of 0.2.

‡Martinez-Yrizar et al. (1992).

§This value is based on Martinez-Yrizar et al. (1992), but Masera et al. (1992) use a root/shoot value of 0.59. The root/shoot value of 0.4 measured by Castellanos et al. (1991) within the same forest type and natural area is used here.

¶Castellanos et al. (1991).

ND No datum.

Table V.4. Total Area, Flux Parameters, and Estimates Used to Compute Net Carbon Balance for Mexico

Land-Cover Type	Parameter	Estimate	Source/Basis
Forest	Root/shoot ratios		
	humid tropical	0.20	Saldarriaga (1985); Masera et al.
	dry tropical	0.40	(1992); Castellanos et al. (1991)
	coniferous	0.20	Cannell (1982)
	broadleaf	0.20	Cannell (1982)
	mangrove forest	0.73	Cannell (1982)
	Proportion of litter & coarse woody debris C vs. phytomass C:		
	humid tropical	0.14	Salati et al. (1991); Uhl et al.
	dry tropical	0.04	(1988); Uhl and Kauffman (1990)
	coniferous	0.04	Assumed
	broadleaf	0.04	Assumed
	mangrove forest	0	Assumed
	C dynamics during fires:		
	% aboveground C to charcoal	3.6	Fearnside (1992); Houghton et al.
	% aboveground C released		(1991a)
	humid tropical	20	Masera et al. (1992)
	dry tropical	40*	Masera et al. (1992)
	coniferous	40	Masera et al. (1992)
	broadleaf	40	Masera et al. (1992)
	% litter released	95	Assumed
	% soil C released	5	Cerri et al. (1991); Sanchez et al. (1983)

continued

Table V.4 (continued)

Land-Cover Type	Parameter	Estimate	Source/Basis
Perturbed forest	Root/shoot ratio	0.2	Saldarriaga (1985)
	Proportion of litter & coarse woody debris C vs. phytomass C	0.33	Saldarriaga (1985); Brown and Lugo (1990)
	Net vegetation C sequestration rate (MgC/ha/yr)	1.0	Assumed†
Grassland/ shrub	Root/shoot ratio	1.6	Singh and Joshi (1979)
	Litter C mass (MgC/ha)	2.0	Kauffmann et al. (1994b)
Pastureland	Root/shoot ratio	1.6	Same as grassland/shrub
	Litter & coarse woody debris C mass (MgC/ha)	2.0	Kauffman et al. (1994b)
	C decomposition post-conversion:		
	decomposition period (MgC/ha)	10	Fearnside (1992); Houghton et al. (1991a)
	% released/yr	10	Assumed
	% soil C released (total)	20	Houghton et al. (1991a)

continued

Table V.4 (continued)

Land-Cover Type	Parameter	Estimate	Source/Basis
Cropland	Root/shoot ratio	0.18	Sanchez et al. (1989)
	Litter & coarse woody debris C	0	Assumed
	C decomposition post-conversion:		
	decomposition period - yr	10	Fearnside (1992)
	% released/yr	10	Assumed
	% soil C released (total)	30	Houghton et al. (1991a); Davidson and Ackerman (1993)
Wetland	Root/shoot ratio	0.73	Assumed similar to mangrove forest
	Proportion of litter & coarse woody debris C vs. phytomass C	0	Assumed
Desert	Root/shoot ratio	0.23	Cannell (1982)
	Litter & coarse woody debris C	0	Assumed
Urban, water			Soil and belowground phytomass were not modeled. These ecosystems were assumed to be in carbon equilibrium for lack of data.

continued

Table V.4 (continued)

*Gonzalez Flores (1992) reports consumption rates of approximately 60% for two fires in tropical dry forest in Jalisco, Mexico.

†As discussed in the text, the severely perturbed forest area is assumed to be in C equilibrium. Within the moderately perturbed forest area, two scenarios are used. Scenario 1: most of this category is in approximate C equilibrium with only a portion equivalent to the land area of forests recently (last 10 years) deforested through timber harvest or wildfires supporting a net C sequestration. Scenario 2: 50% of the perturbed forest area is presumed to be in carbon equilibrium with continued human disturbance balancing vegetation regrowth. The sequestration rate of 1 MgC/ha/yr applies to the remaining 50% of perturbed forest area.

For estimates of soil organic matter C in forest systems, this section relied on global estimates of soil C from Zinke et al. (1984) (Table V.5). Zinke et al. (1984), similarly to Olson et al. (1983), used the globally available estimates of soil carbon and estimated soil C for each continent and the globe in general. The global averages of soil C estimated by Zinke et al. (1984) are similar to the estimates of Kern (1994) and lower than Sombroek et al. (1993). The estimates used by Masera et al. (1992) appear to be low by approximately a factor of two relative to other global estimates.

3. Transition Rates

Obtaining good estimates of the rates of land-cover conversion, especially deforestation, is perhaps the greatest difficulty in estimating C pools and flux in Mexico. The rate of forest conversion in recent decades has most likely not been constant as many factors, including government resettlement and land tenure policies, have served to impede or promote forest clearing (Masera et al. 1995).

For the main analyses of this section, the closed forest deforestation estimate by Masera et al. (1992) is used (0.668 X 10^6 ha/year) (Table V.2). The FAO (1993) estimate of 0.678 X 10^6 ha/year is similar. A direct estimate of the deforestation rate is not available for the perturbed or open forest category (Masera et al. 1992; SARH 1992).

4. Carbon Flux Estimates

To estimate C flux in response to land-use change, parameters were taken from the literature. Where information was not available, assumptions were made based upon the best available knowledge. In some cases, these assumptions are distinctly

Table V.5. Carbon in Mexican Soils by Land-Cover Type*

Land-Cover Type	Carbon in Soil (Depth to 1 m) (MgC/ha)		
	Zinke et al. (1984)	Masera et al. (1992)	Other
Tropical humid forests	104	66	109† 145‡
Tropical dry forest	112	29.5	105†
Temperate coniferous forest	132	109.1	102†
Temperate broadleaf forest	161	29.5	102†
Wetland	234	ND	ND
Mangrove forest	234	ND	ND
Shrub/grassland	77	ND	ND
Desert	25	ND	ND
Cropland	75	ND	ND
Pastureland	75	ND	ND
Perturbed Forest	94	ND	ND

*This section uses data of Zinke et al. (1984) for soil C data.

†Generated by overlaying the forest cover map of Evans et al. (1992) and the map by Kern (1994) then calculating an area-weighted mean carbon density value.

‡Sombroek et al. (1993).

ND No datum

different than those used by Masera et al. (1992) and account for some of the difference in net C emissions between this analysis and Masera et al (1992). Estimates of net terrestrial C flux for Mexico are especially sensitive to certain assumptions made about (1) C uptake by phytomass growth and accumulation in soils and (2) C loss through decomposition and fire (Table V.4). Further, these assumptions are based upon assumptions about the character of vegetation and human perturbation in the land-cover types used. Most of the land area of Mexico is assumed to be in approximate C equilibrium with losses due to fire, harvesting, and decomposition balanced by vegetative growth. The exceptions are recently deforested areas (defined as forests converted to pastureland or cropland within the last 10 years [Table V.2]) and perturbed forests. In both scenarios for the extent of perturbed lands (see Section V.B.1. Land Cover), a net C sequestration rate of 1.0 Mg/ha/yr (Table V.4) was used, with the assumption that C sequestration will be low on most perturbed forestlands because of continuing human and natural disturbance and low site productivity (Masera et al. 1995). Humid forest regrowth following disturbance in the region of Uxpanapa, Veracruz, has been measured at approximately 3.75 MgC/ha/yr (Williams-Linera 1983) during the first seven years following abandonment. This is most likely an upper limit to C sequestration in perturbed forests (Masera et al. 1995). The perturbed forest category of SARH (1992) is not broken out into forest types, so it is difficult to determine the proportion represented by productive humid forest lands. In addition, much of the pastureland and cropland in Uxpanapa has been abandoned (Williams-Linera 1983), and human disturbance pressures in these forests are probably lower than in perturbed forests elsewhere.

Masera et al. (1992) assume that 20-40% of aboveground phytomass C is carbonized during land-clearing fires, with the remainder either passing to the atmosphere immediately through combustion or slowly through decomposition. An alternative estimate of 4%

or less has been suggested (Table V.4) (Houghton et al. 1991a; Fearnside 1992; Kauffman et al. 1994a). Although values higher than 4% may be reasonable for areas that are repeatedly burned, values as high as 40% are probably extreme. This section uses an estimate of 8% to reflect the lower estimate of carbonization through repeated fires.

Data to estimate long-term C storage in wood products and landfills are not available for Mexico. Due to this lack of information, this section makes no estimate of C storage in landfills, and C storage in wood products is estimated only for current year harvest levels. Clearly, ignoring C storage in landfills and wood products will lead to an underestimate of total C storage in Mexico. For current year withdrawals, estimates of harvest volume for Mexico were taken from three sources (UNAM 1991; Masera et al. 1995; WRI 1993). The proportion of wood products from each of four forest types (conifer, broadleaf, humid tropical, and dry tropical) are given by UNAM (1991). The volume of wood from each forest type was converted to mass of C using wood density estimates of 0.5 for conifer species and 0.6 for all others (Chudnoff 1984; Masera et al. 1992).

C. Results

An estimated 54% of the total TEC of Mexico is in forests (Table V.6), which cover 36% of the total land area (Table V.1). Temperate coniferous forests are the largest reservoir at ~13% of the country's TEC, followed by humid tropical forests with ~11%, dry tropical forest with ~9%, and broadleaf temperate forests with ~7%. Although perturbed forests have been assigned relatively low C density values, they are estimated to contain ~13% of the TEC of Mexico due to their large area.

Table V.6. Carbon Pools of Mexico by Land-Cover Type, 1990*

Land-Cover Type	Carbon Pool (PgC)					
	Phytomass			Litter /CWD	Soil	Total
	Total	Above-ground‡	Below-ground			
Forest	4.56†	3.72	0.84	0.50	8.44	13.50
Woodland/ scrub	1.33	0.51	0.82	0.13	5.11	6.57
Pasture-land	0.19	0.07	0.12	0.14	3.00	3.33
Cropland	0.08	0.068	0.012	0.015	1.02	1.115
Wetland	0.002	0.001	0.001	0	0.29	0.292
Mangrove forest	0.015	0.009	0.006	0	0.12	0.135
Other	0.008	0.007	0.001	0	0.097	0.105
Total	6.185	4.385	1.800	0.785	18.077	25.047

* Values developed for this Mexico case study based upon Tables V.1 through V.5.

† Forest C pool was computed by multiplying 71.28 X 10^6 ha (Table V.1) times the area-weighted mean C density, 64 MgC/ha, based upon values in Tables V.2 and V.3 and appearing in Table V.7.

‡ Aboveground phytomass values were determined by partitioning the total phytomass values with the root/shoot ratios in Table V.3, e.g. Mangrove forest: (0.015 PgC) ÷ (0.73 roots + 1.0 shoots [Table V.3]) = 0.009 PgC in aboveground phytomass.

Woodland/scrub ecosystems are estimated to hold only ~26% of the national C pool (Table V.6) although this ecosystem is approximately equivalent in land area to that of forests (Table V.1). Pastureland is estimated to contain ~13% of TEC, primarily as soil organic matter, due largely to the extensive area of this land-cover type. As previously discussed, much of the perturbed forest and woodland/scrub categories are presumed to include areas used for pastureland but which carry significant woody phytomass. Croplands, which are assumed to lose more soil organic matter than pasturelands after conversion from forest (Brown and Lugo 1990; Houghton et al. 1991a; Davidson and Ackerman 1993) and which represent ~7% of the area of Mexico, contain an estimated 4% of the national TEC.

The area-weighted mean C density for phytomass, litter/CWD and soil in each major land-cover type (Table V.1) was calculated (Table V.7). Although forest C densities for phytomass are estimated to range as high as 150 Mg/ha in tropical humid forest (Olson et al. 1983), the much larger areas of forests in Mexico with relatively low phytomass C density (conifer, broadleaf, and dry tropical) and perturbed forests dominate the forest category (i.e. resulting in an area-weighted mean of 64 Mg/ha, Table V.7). If perturbed forests are not included in this calculation, the area-weighted mean phytomass C density of forests is 74 Mg/ha.

Most of the land surface of Mexico is estimated to be in C equilibrium, though this is a tenuous assumption (Lugo and Brown 1992; Brown et al. 1992). Fluxes of C were assigned (Table V.8) to (1) land-cover conversion (e.g., fires associated with deforestation); (2) long-term losses due to decomposition after land conversion (e.g., slash or soil organic matter decomposition); and (3) C sequestration through regrowth of a portion of the perturbed forest and pastureland classes. The total annual C flux to the atmosphere from deforestation was estimated at 75.8

Table V.7. Area-Weighted Mean Carbon Densities by Major Land-Cover Type in Mexico*

Land-Cover Type	Carbon Density (MgC/ha)			
	Phytomass	Litter/ CWD	Soil	Total
Forest	64	7	118	189
Woodland/scrub	20	2	77	99
Pastureland	5	4	78	87
Cropland	6	1	78	85
Wetland	2	0	234	236
Mangrove forest	30	0	234	266
Other	14	0	20	34
Total Area-Weighted Mean	32	4	92	128

* Values developed from Tables V.1 through V.5.

Table V.8. Carbon Flux for Mexico*

Component	Reported C Flux (TgC/yr) [base year]			
	This section [1990]	Makundi et al. (1992) [1985]	Subak et al. (1993) [1985-1988]	WRI (1993) [1989]
Land-base flux				
Phytomass	+4.0 to +12.0	+3.5‡	ND	ND
Litter and CWD	+0.2	ND	ND	ND
Soil	+0.2	ND	ND	ND
Total land-base flux	+4.4 to +12.4	ND	ND	ND
Land-use change				
Removals	NC	-8.6§	ND	ND
Emissions:				
Prompt	-30.8	-27.9	ND	ND
Inherited	-45.0	-26.1	ND	ND
Total land-use change	-75.8	-62.6	ND	ND
Net flux of C between terrestrial ecosystems and the atmosphere¶	-63.4 to -71.4	-59.1	-55.9	-60.9
Fossil fuels				
Fossil fuel as CO_2-C	NC	-83.1¶	-74.4	-93.7
Cement manufacture C	NC	-3.2¶	-3.1	-3.6
Total industrial emissions	NC	-86.3	-77.5	-97.3
Total nation	-149.7 to -157.7#	-145.4	-133.4	-158.2

*Positive values are C uptake and negative values are C emission to the atmosphere.
‡For forests only (Makundi et al. 1992).
§Conversion of Makundi et al. (1992) wood removal values (lumber, paper, posts, and fuelwood) to equivalent phytomass C quantities.
¶From Masera et al. (1992).
#The "total nation" values for "this section" utilizes the Makundi et al. (1992) values for total industrial emissions of -86.3 TgC/yr; values from Subak et al. (1993) and WRI (1993) could also be used resulting in a wider range of national totals.
NC Not calculated for this section because of insufficient data; however, the value is not assumed to be zero.
ND No datum.

Tg/yr (Table V.8) of which 45.0 Tg/yr are estimated to be inherited emissions. The remaining 30.8 Tg/yr are prompt C emissions arising directly from base-year land conversions, predominantly through fires.

D. Discussion

For Mexico, the estimate of 30.8 Tg/yr for prompt C emissions and 75.8 Tg/yr combined (prompt + inherited for 1990) emissions are higher than those estimated by Makundi et al. (1992) (based on work by Masera et al. 1992) of 27.9 and 62.6 TgC/yr, respectively, for 1985 (Table V.8). The difference in base years between the two studies has a negligible effect on the estimates since most of the deforestation data is averaged for the 1980s. Differences in land area between the two dates (1985 and 1990) are well within the uncertainty associated with any single-date estimate. Also, the fact that this section includes all Mexican lands, rather than only closed forests, has little effect on emissions estimates since most non-forest lands are assumed to be in approximate C equilibrium.

The emission differences between this section and Makundi et al. (1992) are primarily attributable to two factors. First, this section uses much lower estimates of percent phytomass C converted to charcoal during fires (8% vs. 20-40%). Second, this section generally used higher phytomass C estimates for forests and much higher soil C estimates. These two factors account for approximately 70% of the difference between the estimates of this section and those of Makundi et al. (1992) and Masera et al. (1992).

A few comparisons are possible between the Olson et al. (1983) estimates for C density and the limited data published for Mexican forest sites (Table V.3). Castellanos et al. (1991)

estimated total phytomass (above and belowground) in a dry tropical forest in Jalisco state at 104.5 Mg/ha. If half of this amount of phytomass is C (as commonly assumed), then about 52 MgC/ha is comparable to Olson's estimate of 50 MgC/ha. Martinez-Yrizar et al. (1992), working in the same area, estimated aboveground phytomass at 85 Mg/ha or by the same assumption, 42.5 MgC/ha. At a root/shoot ratio of 0.42 (Castellanos et al. 1991), total phytomass C would be 60 MgC/ha. For mature Mexican humid tropical forest, no comprehensive studies of phytomass are published, yet the Olson value of 150 MgC/ha is at the low end of C estimates based upon stand-table data from Veracruz (M. Ricker, Yale University, pers. comm., 1993). The Olson et al. (1983) estimates appear to concur reasonably well with the few published C density values reported for Mexico.

The soil C estimates used by Masera et al. (1992) are lower by a factor of approximately two relative to estimates by Zinke et al. (1984). The Zinke estimates use globally available soil C data for calculating values for each continent and the globe. The global averages of Zinke et al. (1984) are similar to the estimates of Kern (1994) and lower than Sombroek et al. (1993) (Table V.5).

Studies are underway in Mexico to improve the estimates of phytomass and soil C densities (Cairns 1994) through satellite-based mapping and field TEC measurements. Until they are available, it is best to consider that the estimates of Makundi et al. (1992) and this section define a range within which the actual level of C emissions lie.

Emissions of C may be partially offset in Mexico through sequestration in growing vegetation. Although there is little information available on the status of second growth forests or regrowth of vegetation in perturbed forests, this section defines

an upper and lower limit of C sequestration. This rough approximation suggests that C sequestration may range from 4 to 12 TgC/yr (Table V.8), equivalent to 5 to 16% of emissions due to land-use change. Makundi et al. (1992) estimated that 3.5 TgC/yr were sequestered annually on recently deforested lands within the four closed forest categories of Mexico.

Opportunities exist in Mexico for promoting conservation and sequestration of C through ecosystem management that would contribute to global greenhouse gas mitigation. Recent changes in national policies (Masera et al. 1995) may remove government support for forest conversion to pastureland. Further, changes in land-tenure laws may also encourage long-term forest management.

Masera et al. (1995) suggest that investments in improved management of temperate and moist tropical forests in Mexico are economically feasible and would, at the same time, provide substantial C sequestration and conservation. Masera et al. (1995), also considered enhanced natural area protection, restoration planting, pulpwood plantations, and improved wood-burning stoves as viable mechanisms for sequestering or conserving C. These authors estimate an upper limit of 60 TgC/yr could be sequestered over the next 20 years at a cost of approximately $5.1 billion if all examined options were implemented. This represents a substantial fraction of the annual national energy emissions of CO_2-C (Table V.8), although the energy sector emissions may double or even triple in the next 40 to 100 years (Mendoza et al. 1991; Masera et al. 1995).

An analysis of the potential of reforestation practices in 34 forested nations of the world by Dixon et al. (1993) show that reforestation practices in Mexico could sequester an average of about 100 MgC/ha at $4.50/MgC based on initial costs of plantation establishment. Among the 34 forested nations analyzed,

Mexico's reforestation cost per MgC was one of 12 with costs below $5/MgC.

Carbon may also be sequestered in wood products. This section estimates that approximately 8.6 TgC/yr of C were removed from Mexican forests in 1990 as wood products. The proportion of this C which is quickly converted into CO_2 through burning or decomposition is not known, though fuelwood comprises approximately 70% of all wood removals. Due to these uncertainties, the 8.6 TgC/yr removed in wood products was not included in the C budget for Mexico. O. Masera (Universidad Nacional Autonoma de Mexico, pers. comm., 1994) suggests that solid wood products may last at least an average of 5 years in Mexico. If even a small proportion of the 8.65 TgC/yr removed as wood products each year is used as durable products, this represents a significant C pool, leading to an underestimate of C storage in Mexico.

Estimates of net C emissions from Mexico's terrestrial ecosystems by all studies range from 56 to 71 TgC/yr as compared to industrial emissions of 77 to 97 TgC/yr (Table V.8). These emissions due to land-use change represent approximately 0.25% of the entire C pool in all ecosystems of Mexico (Table V.6) being transferred to the atmosphere each year. The estimates of land-use change emissions represent approximately 3% of estimated global emissions of C from deforestation (WRI 1993).

Of the total C emissions from land-use change in Mexico, disturbance of the humid tropical forests are the major source of C emissions. Deforestation in Mexican tropical forests account for approximately 75% of net deforestation emissions. Most emissions come from land conversion of forests to pastureland, cropland or other non-forest activities rather than from harvesting. Little more than 2% of total emissions are derived from forests that have been logged versus a 16% contribution from forest fires.

Recent estimates of deforestation rates in Mexico have largely been site- or region-specific (Dirzo and Garcia 1992; Masera et al. 1992). The Masera et al. (1992) estimate of total area deforested (.668 X 10^6 ha/year, Table V.2) is about the same as FAO's (1993) estimate. Other deforestation estimates in Mexico range from 365 X 10^3 to 1500 X 10^3 ha/yr (Cairns et al. 1995). FAO (1993) stratified forest types in a manner not readily comparable to other available sources of information for Mexico. For example, an exact equivalence between the forest zones of FAO (1993) and the forest types of Masera et al. (1992) is not possible because the zones and types do not match in area or definition. Deforestation rates in the wet and moist zones of the FAO (1993) classification, however, are lower than estimated by Masera et al. (1992) for the humid tropical forests (evergreen and semi-evergreen tropical forests). Conversely, deforestation in the hill and montane zones is higher than the conifer and oak types of Masera et al. (1992).

E. Conclusions

This section reports that estimated net emissions of C from Mexican terrestrial ecosystems for 1990 range from 63.4 to 71.4 TgC or about 44% to 49% of the total national C emissions as estimated by Makundi et al. (1992). The net C emissions estimated in this section are higher than in studies by Makundi et al. (1992), Subak et al. (1993) and WRI (1993). Using any of these studies, however, it is apparent that land-use change is driving a significant loss of the C capital of the nation of Mexico and is making a contribution to the net C flux to the atmosphere on a global basis.

In Mexico, as with many other tropical nations, C emissions from land-use change are substantial when compared to fossil fuel C emissions. Mexico cannot long sustain the second highest areal

extent of deforestation in Latin America (FAO 1993). However, conservation of remaining forests may be difficult to achieve based on trends in Mexico's agricultural expansion.

The relatively close agreement between results from this section and other sources is not necessarily an indication of accuracy or precision. There is considerable uncertainty in the magnitude of both source and sink components of the Mexican terrestrial C cycle, and the results of this study must be considered extremely tentative. Several assumptions employed in this section contribute to the uncertainties in this analysis.

First, the land cover area estimates used in this study are preliminary. Both this section and Masera et al. (1992) use data from SARH (SARH 1986 and SARH 1992 respectively), which may lead to common errors.

Second, as discussed previously in this section and at greater length earlier in Section II.B.2.c, this section assumes that most undisturbed lands are in C equilibrium with the atmosphere. This assumption has been challenged globally by Lugo and Brown (1992). Carbon equilibrium in mature forests is also implicit in the assumption that forests disturbed in the past ten years are considered to have C sequestration potential while older perturbed forests are not modeled as C sinks. Specifically, this section employs one scenario that assumes that only forests recently and moderately perturbed (i.e., including perturbation by wildfire and timber harvest, but not by conversion to agricultural use) are experiencing net C sequestration at the rate of 1 Mg/ha/yr (see part 1. Land Cover). Another scenario assumes that 50% of the recently perturbed forest is sequestering C at 1 Mg/ha/yr. Both the assumption that older perturbed forests are in equilibrium and the estimate of C sequestration rate may be in error.

Third, this section uses the relative proportions of pastureland and croplands estimated by Masera et al. (1992) to estimate forestlands recently deforested. This was done even though the total area of non-forestland estimated by Masera et al. (1992) (107.3×10^6) is different from the total estimated by SARH (1992) (51.5×10^6 ha) used here. The assumption that the proportions used by Masera et al. (1992) can be applied to the SARH data may not be valid.

Fourth, this study relies on phytomass C densities from Olson et al. (1983, 1985). Olson C densities are based on limited numbers of field measurements extrapolated to continental scales. Although the low Olson C density estimate are in reasonable agreement with the few available published values for Mexico, their accuracy and relevance to Mexico are uncertain.

Fifth, the assumptions used here regarding loss of soil C after conversion of forest to pastureland or cropland are strongly debated in the scientific literature. There is neither consensus as to the magnitude or, in some cases, the sign of C flux after forest conversion (Davidson and Ackerman 1993, Houghton et al. 1991b): A number of factors are critical in controlling ecosystem response to forest conversion. Clearly, however, the type of conversion coupled with the severity and duration of disturbance (e.g., repeated fires, mechanical clearing, and cultivation) will lead different C dynamics post-disturbance (Brown and Lugo 1990).

Finally, the equation of land-use and land-cover change with deforestation is a recognition of our lack of data on the ultimate fate of disturbed land. It is known that indigenous Mexican Mayans have managed southern forests for several centuries, creating a patchwork of secondary forests. If, due to lower population densities today than in the past, the net effect is an increase in growing stock, then a large amount of C may be actively sequestered in tropical Mexican forests. Not all land

cover change has C dynamics impacts similar to deforestation, e.g. selective harvesting.

Although these may be the major uncertainties involved in this study, they are likely not the only ones. This section has attempted to incorporate improvements in estimates of C dynamics which have become available since the studies of Masera et al. (1992) and Makundi et al. (1992) were completed and to expand the scope of the C budgets. At present, it is prudent to consider the results of this section and those of the previous studies to define a range within which the actual level of C pools and flux lie. Because data are lacking to confirm several assumptions presently employed, research is required in each of these areas.

Box 4: Brazil

Brazil lies between latitudes 5°N and 32°S and longitudes 35°W and 75°W, occupies an area of 845 X 10^6 ha, and dominates South America. It is the fifth largest nation in the world in land area behind the former Soviet Union (FSU), Canada, China, and the United States. The nation is divided into 27 states and the Federal District of Brasilia, the capital (Cottle et al. 1990) (Figure VI.1).

In 1990, the population of Brazil was about 150 million people corresponding to a population density of 18/km^2. By comparison in 1990, the population density of FSU was 13 people/km^2, China, 122, Canada, 29, and the U.S., 27 (WRI 1992). In Brazil, however, 58% of the people live in the five most southern and southeastern states with 25% living in five metropolitan areas located in these states (NYT 1988). In total, Brazil has 14 cities with over 1 million people each. The annual growth rate of the population is 2.2% which projects to a population of 165 million by 1995 (WRI 1992).

Brazil was explored and settled by the Portuguese starting in about 1500 AD. Today the Portuguese influence remains strong within Brazil, and Portuguese is the official language. However, many remnants of the indigenous Indian populations are scattered through the nation with higher concentrations of these people in the Amazon region (Eden 1990).

Currently, Brazil has a democratically elected government, though prior to 1985, Brazil had a long period of military rule. New elections are scheduled for 1994. Economically, Brazil is considered a developing nation with a 1990 GNP of $U.S. 2,550/capita compared to $U.S. 9,211 for the FSU, $US 360 for China, $U.S. 19,020 for Canada, and $U.S. 21,100 for the U.S. (WRI 1992). In the early 1990s, Brazil's economy has been in a recession with inflation rates in 1993 near 40% per month (EIU 1994).

Brazil has the largest area of forest of any of the nations in the tropical latitudes, over 370 X 10^6 ha of closed forests plus 70 X 10^6 ha of secondary forests (Stone et al. 1994) (Tables VI.1 and VII.1). Thus, Brazil's forest area is several times that of Zaire at 113 X 10^6 ha; Indonesia at 110 X 10^6 ha; and Peru at 68 X 10^6 ha, the next most forested nations in the tropics (FAO 1993).

The climate of Brazil has four broad geographic regions:

1) Tropical humid in the rolling lowlands (<300 m of elevation) of the Amazonia area to the north (Figure VI.1). The annual precipitation ranges from 1500 to 3000 mm with the primary wet season occurring from November through April (Eden 1990). Mean monthly temperatures vary between 25 to 28 °C year around. The natural vegetation type is predominantly closed moist forest (Stone et al. 1994). About 10% of closed moist tropical forest has been deforestated during the last several decades (Fearnside 1993). These areas are now in secondary forests, pasture, shifting subsistence agriculture, dam reservoirs, and open-pit mines (Fearnside 1992).

(2) Cooler tropical humid in the Atlantic coast (lat5°S to 15°S) at elevations near 500 m, though with coastal mountains up to 2000 m (Figure VI.1). The temperatures vary from 21 to 24 °C and annual precipitation ranges from 1000 mm to 4000 mm, mostly in December through March (though lat5°S to 15°S, there is a rainy season from April through July). Droughts, however, are frequent throughout the region. Vegetation types are a mix of cerrado (i.e., savannah) and woodlands. Though in many areas much land is in a degraded condition (Stone et al. 1994), subsistence farming and sugar cane production widely occur.

(3) Tropical semi-humid in the central cerrado region at elevations near about 1000 m (Figure VI.1). For the cerrado plateau, the annual precipitation varies between 1000 to 2000 mm (primarily in December through March) with annual temperatures averaging 20 to 28 °C. Vegetation types are dominated by cerrado (a mix of campo limpo or grassland to woody cerrado) with widespread clearing for commercial farm crops such as soybeans and corn (Stone et al. 1994).

(4) Cooler subtropical to warm temperate humid conditions at elevations below 800 m in the south though interspersed with higher elevations in mountain ranges (NYT 1988; Cottle et al. 1990). The southern subtropical area has an annual precipitation rate between 1000 and 2000 mm distributed year around and with mean monthly temperatures generally between 10 °C in the winter up to 27 °C in the summer. Vegetation types of the lower elevations are grasslands widely used for farming. Mountain areas have degraded closed forests extensively used for farming with some degraded lands that have reverted to secondary forests (Stone et al. 1994).

The tropical region of Brazil is dispersed within the basin of the world's largest river system, the Amazon. In total, the basin covers 705 X 10^6 ha (NYT 1988), and 66% is within Brazil (Fearnside 1992). The river has an annual discharge of 5.5 X 10^{12} m^3 (Sioli 1975). Comparable figures for the Mississippi River in the U.S. are 325 X 10^6 ha in area drained, an annual discharge of 0.5 X 10^{12} m^3 of water, and about 0.8% of the world's total fresh water (Goulding 1980).

Brazil's biodiversity is one of the richest in the world with an estimated total of 30,000 species of higher plants (470+ tree species) and over 1 million animal species including insects, birds, fish, rodents, and others (Eden 1990). Conservation of these unique ecological features along with sustainable development has become one of the greatest contemporary environmental concerns for both natural resource managers and scientists in Brazil as well as around the world.

VI. Brazil Case Study

A. Introduction

Brazil plays an important role in the tropical and global C cycle. This importance emanates from Brazil's (1) large geographic area (Figure VI.1), placing it fifth in size among all nations at about 850 X 10^6 ha (WRI 1992); (2) over 350 X 10^6 ha of C-dense, closed moist forest (Stone et al. 1994 and Table VI.1), the largest in the tropics (FAO 1993); and (3) intense level of land-use change associated with the nation's attempt to improve its developing economy (Box 4).

The most renowned land-use change in Brazil is deforestation of the tropical forests to meet land needs for more agriculture, pastureland, logging, mining, dams, roads, and settlements as the nation strives to develop economically. The level of deforestation in Brazil has been one of the world's highest during the past decade ranging from 1 to 2 X 10^6 ha/yr (INPE 1992). The annual deforestation rate for the total tropical regions of the world during the period 1981-1990 was 15.4 X 10^6 ha/yr (FAO 1993). Fragmentation of the remaining forest habitat is also a concern (Skole and Tucker 1993).

These characteristics make Brazil a most useful case study to assess the contribution of land use and changes in land use to a national C flux. The main focus of the Brazil study is on (1) the C pools of terrestrial ecosystems in Brazil; (2) the net flux of CO_2 through ecosystem phytomass and soils; and (3) the effect on C pools and flux associated with human activities, predominantly land-use change. All data on pools and fluxes are for the nominal base year of 1990. Information and data for the study come from a review of the technical literature and contacts with scientists engaged in ecological research in Brazil.

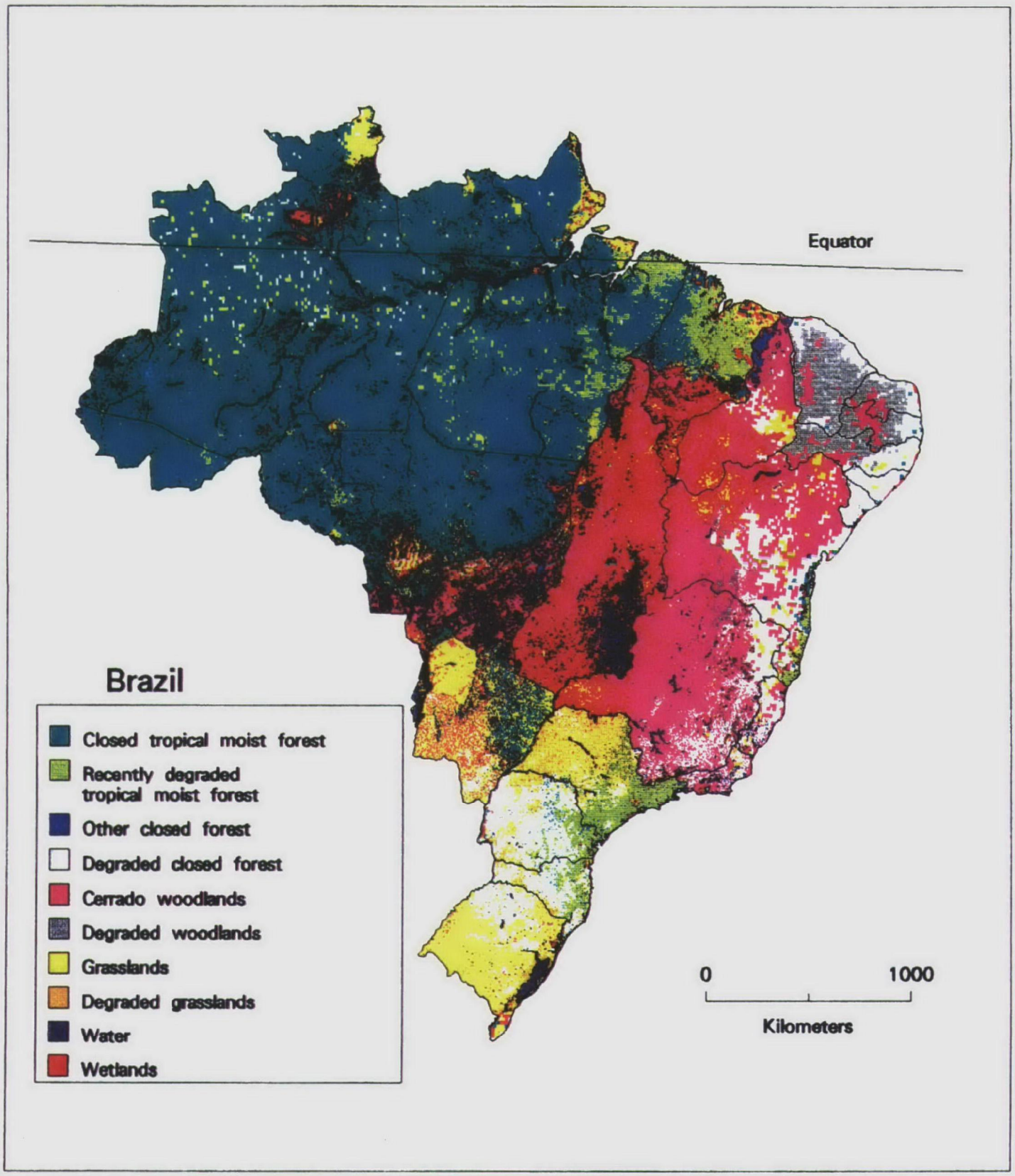


Figure VI.1 Vegetation map of Brazil developed by Stone et al. (1994).

Table VI.1. Vegetation and Land-Use Types, Brazil, 1994*

Vegetation and Land-Use Type	Area ($X 10^6$ ha)	Area (%)
Closed moist forest (TMF)	352.2	42
Recently degraded TMF		
Secondary forest	17.4	2
Degraded forest/mixed agriculture	19.4	1
Pastureland	15.1	2
Other closed forest	16.4	2
Degraded closed forest		
Agriculture	99.7	12
Secondary Forest	17.6	2
Cerrado woodland	155.6	19
Degraded woodland	33.0	4
Savannah/grassland	74.0	9
Degraded savannah (converted to agriculture)	17.9	2
Wetland/mangrove	12.4	1
Total	830.7	100

*Stone et al. (1994).

B. Methods

A national biotic C flux study is essentially an accounting of the annual net exchange of C between the atmosphere and the terrestrial ecosystems of that nation. For Brazil, this study considered both processes that take up C and those that release C, and it encompasses the entire geographic region of the nation. Many previous studies for tropical regions consider either only the uptake of C in forests (e.g., Brown et al. 1992; Lugo and Brown 1992) or the release of C, particularly through human activities such as deforestation (e.g., Detwiler and Hall 1988; Houghton et al. 1991a and b). For Brazil, most analyses of phytomass C dynamics have only considered the nation's Amazon region (e.g., Fearnside 1992).

1. Conceptual Model

The approach for the Brazil case study is based on a simple conceptual model of ecosystem C storage and flux (Figure VI.2). The primary C pools in the model are the atmosphere, phytomass, litter and coarse woody debris (CWD), and soil. Flux is represented as a transfer of C between these pools that occur as a result of land-use change, natural disturbance such as by storms (Nelson et al. 1994), or recovery from past changes or disturbances by plant growth and accumulation of organic matter. The key flux is that between components of the land and the atmosphere, i.e., through growth (carbon removed from the atmosphere), decomposition and deforestation/burning (carbon emitted to the atmosphere) (Figure VI.2).

2. Vegetation and Land-Use Types

The conceptual C model was applied to each of the vegetation types for a recently completed vegetation map of Brazil (Figure

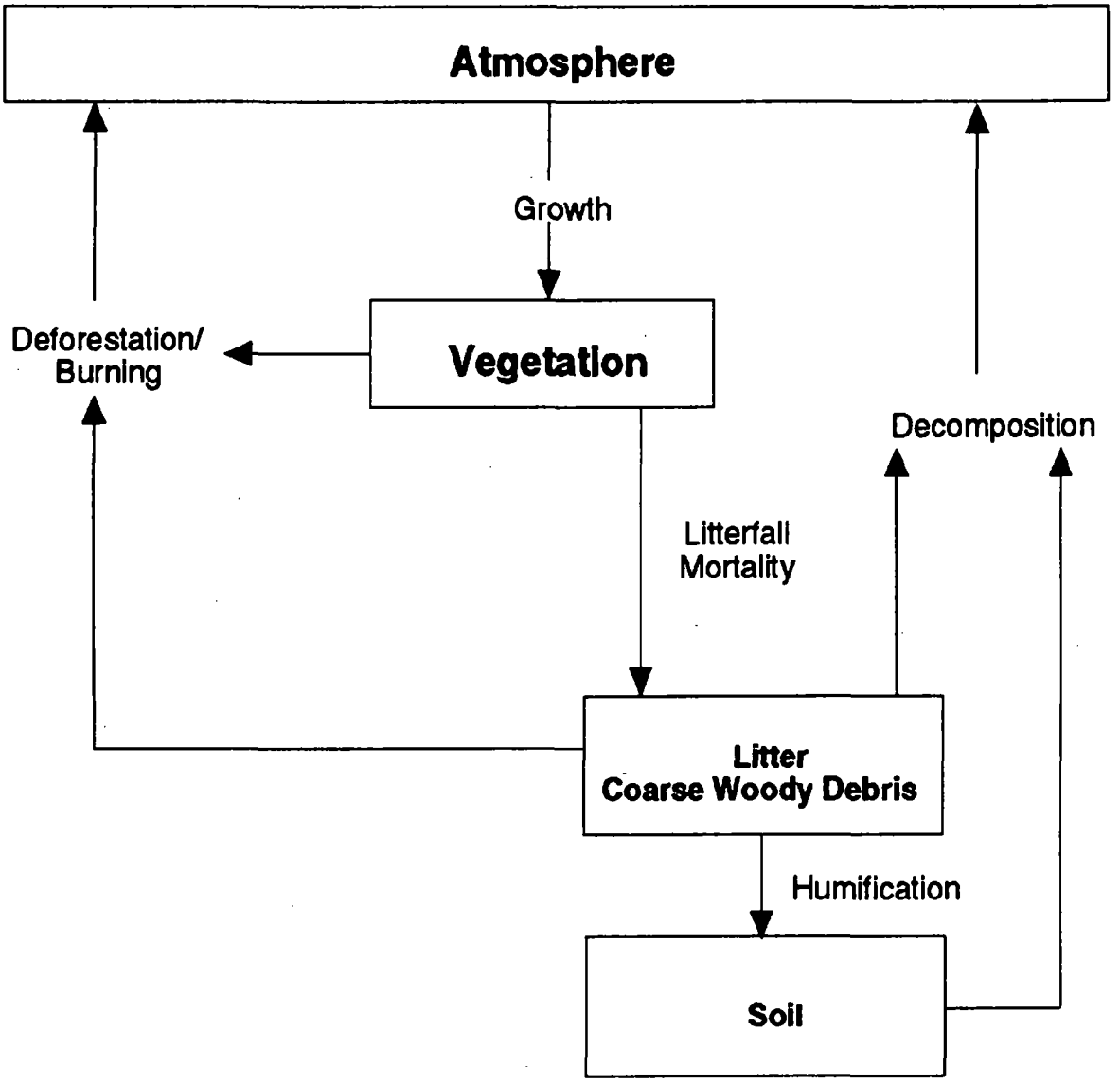


Figure VI.2. Conceptual model of biotic net carbon balance.

VI.1) (Stone et al. 1994). Other vegetation maps of Brazil were considered and found less useful for this analysis (see Section VI.D.2.).

The map by Stone et al. (1994) was based primarily on Advanced Very High Resolution Radiometer (AVHRR) satellite data from the late 1980s and early 1990s with a resolution of approximately 1.1 km. These data were supplemented by higher resolution satellite imagery available for certain sections of South America, by photographs, by earlier potential vegetation maps, and by field observations. Because cloud-free, 1.1 km data were not available for the whole nation, a three-year weekly data set of 15 km Global Vegetation Index (GVI) data was also utilized for areas with missing data (Stone et al. 1994). This explains the different pixel sizes in the vegetation map (Figure VI.1).

The two degraded forest types (Table VI.1) were subdivided in order to more readily estimate their C densities. Stone et al. (1994) use the term degraded in connection with any of the types to include "areas which have been altered or converted from natural or primary vegetation by man, grazing or for cultivation." The degraded forest vegetation classes are very heterogeneous and can include land uses with quite different C densities.

First, the degraded tropical moist forest (TMF) type was split into three subdivisions: secondary forest, degraded forest with mixed agriculture, and pastureland. Of the total area (51.9 X 10^6 ha; Table VI.1) in this type, 9.4 X 10^6 ha are located outside the Amazon basin are dealt with below. Another 12.3 X 10^6 ha are in the states of Para and Maranhao in areas that have been settled for a long time. The resulting landscape has been heavily influenced by human occupation and consists of a mix of small scale agriculture, fallow fields, palms, and degraded secondary vegetation. In this study, this diverse landscape is called "degraded forest/mixed agriculture" (Table VI.1).

An additional area of degraded TMF of about 30.2 X 10^6 is located elsewhere in the Amazon basin. This area includes secondary forest and, although it could not be clearly distinguished from the AVHRR data, is also believed to include areas of pasture (Tom Stone, Woods Hole Research Center, pers. comm., 1994). A number of references from the literature indicate what might be a plausible weighing between the two. A Landsat Thematic Mapper (TM) analysis in Para by Lefebvre and Stone (1994) showed that about 45% of the area of cleared or altered forest was in secondary forest. Fearnside (1992) estimated that 63% of deforested areas Amazon-wide would develop into secondary forest and degraded pasture. Degraded in this context usually implies invasive secondary vegetation including woody shrubs and trees. In Paragominas County in Para, Mattos and Uhl (1994) estimated that up to 50% of previously cleared pastures had been abandoned. Hecht (1993) estimated 50% of pastures throughout the Amazon had been abandoned, presumably to secondary vegetation. Based on these studies, the area of degraded TMF was partitioned into 50% each (i.e., 15.1 X 10^6 ha) for secondary forest and pastureland (though in Table VI.1 the area for secondary forest is 17.4 X 10^6 ha because 2.3 X 10^6 ha were added for plantations as noted below).

Two other studies, however, illustrate the uncertainty in this partitioning. A Landsat TM study in Rondonia estimated that only 33% of deforested areas were in secondary forest (Skole et al. 1994), but another Landsat TM study in western Para found that 70-80% of cleared areas were occupied by secondary forest (Moran et al. 1994). For this analysis of the C pools of Brazil, exact partitioning of this 30.2 X 10^6 ha vegetation type has some influence on the results, but not a critical one. The impact on C flux, however, is potentially more significant as shown in the sensitivity analysis for the importance of secondary forests (see Section VI.D.3).

Finally, 9.4 X 10^6 ha of degraded TMF are located outside of the Amazon basin along the Atlantic coast in eastern and southeastern Brazil (Table VI.1 and Figure VI.1). For this area, 2.3 X 10^6 ha were allocated to tree plantations and secondary forest (Camara 1991; H.T. do Couto, Universidade de Sao Paulo, pers. comm., 1992) and the remainder to degraded forest/mixed agriculture. Tree plantations were thus included in the secondary forest type bringing the total in Table VI.1 to 17.4 X 10^6 ha (15.1 from above plus 2.3 here).

Second, the definition of the degraded closed forest vegetation type includes both secondary forest and agricultural areas. Because the C densities of these land uses are quite different, the type was subdivided into these two land uses using proportions reported by Fonseca (1985). He estimated that the Atlantic forest had been converted to approximately 85% agriculture and 15% secondary forest so that the resulting areas were 99.7 and 17.6 X 10^6 ha, respectively (Table VI.1).

The combination of information sources just described produced the following set of major vegetation types or land-use types used for this study (Table VI.1):

a. Closed tropical moist forest (TMF)

b. Recently degraded TMF
   - Secondary forest
   - Degraded forest/ mixed agriculture
   - Pastureland

c. Other closed forest

d. Degraded closed forest
   - Subdivided into:
     - Agriculture and
     - Secondary forest

e. Cerrado woodland

f. Degraded woodland

g. Savannah/grassland

h. Degraded savannah (converted to agriculture)

i. Wetland/mangrove

3. Brazil's Carbon Pools

Estimates of the terrestrial C pools of Brazil depend upon two primary types of information: (1) the area of major vegetation and land-use types and (2) reported data on the C density in MgC/ha within each area. Areas of vegetation came from the map by Stone et al. (1994).

The biotic C content in each vegetation or land-use type included estimates of three major components: phytomass, woody debris (including litter and course woody debris [CWD]), and soil. An important source for C density data was a report compiled by Olson et al. (1983) characterizing C in the world's phytomass. This global scale study developed a 0.5° latitude X 0.5° longitude vegetation map based on data from the late 1970s. Plant mass and C were estimated for 47 vegetation types based on a very wide variety and extensive number of ecosystem studies (Olson et al. 1983). Some C density values were revised in a subsequent report (Olson et al. 1985), and these data were also used where appropriate. Finally, C density values were assigned to the Stone vegetation types from the most similar types in the Olson classification system (Table VI.2).

Though the Olson (1983, 1985) C density data for the terrestrial ecosystems of the world are widely used, more accurate site-specific data for Brazilian ecosystems is a definite research need. To illustrate, some of the vegetation types in the map by Stone et al. (1994) had no counterpart in the Olson map so that C density estimates came from other sources. One was degraded woodlands, and here the derivation of the C density estimate was from several references. Tropical woodlands are most often degraded by excessive burning which lowers the phytomass density and opens the woody vegetation (Eiten 1972; Coutinho 1982; Frost and Robertson 1985). It was assumed that if intact woodland

Table VI.2. Carbon Density in Phytomass by Vegetation and Land-Use Type, Brazil

Vegetation and Land-Use Type*	Phytomass C (MgC/ha)		
	Olson†	Fearnside‡	Brown & Lugo§ Kauffman#
Closed tropical moist forest (TMF)	200	191	137§
Recently degraded TMF			
Secondary forest	40	ND	ND
Degraded forest/ mixed agriculture	25¶	ND	ND
Pastureland	10‡	ND	ND
Other closed forest	60	172	ND
Degraded closed forest			
Agriculture	8	ND	ND
Secondary Forest	40	ND	ND
Cerrado woodland	30	22	ND
Degraded woodland	20#	ND	ND
Savannah/grassland	9	ND	3.4▲
Degraded savannah (converted to agriculture)	8	ND	ND
Wetland/mangrove	30	190	ND

*Stone et al. (1994).
†Olson et al. (1983 and 1985).
‡Fearnside (1992).
§Brown and Lugo (1992). Estimated from their published value for above-ground phytomass by using a root/shoot ratio of 0.2 and C concentration of 0.5.
¶Author's approximation, see text for explanation.
#Deduced from several sources, see text for explanation.
▲Kauffman et al. (1994b).
ND No datum.

contained 30 MgC/ha and if agricultural areas contain 8 MgC/ha (both values from Olson et al. 1983 and 1985) then degraded woodlands should be intermediate, i.e., approximately 20 MgC/ha (Table VI.2).

The degraded forest/mixed agriculture type also had no counterpart in the Olson classification. This type actually represents an intermixed variety of different types of vegetation and land uses. No data were available on the C density for this type. The best approach seemed to try to approximate an average C density that could be used for the whole type. Similar to degraded woodlands, it seemed that an appropriate average C density should be somewhere between that for secondary forest (40 MgC/ha) and that for pastureland (10 MgC/ha). A mid-point value of 25 MgC/ha was used. The C density estimate for pastureland was taken from Fearnside (1992).

These values (the Olson set plus the estimates for degraded woodlands and Fearnside's value for pastureland) furnished one series of C densities (Table VI.2). Carbon values from other sources were also used in order to provide a range of C pool estimates for some vegetation and land-use types. This approach reflects the uncertainty in the available data that results from the complexity, size, and diversity of the nation and its vegetation. By using a variety of data sources, the objective was to produce a range of results that would bound this uncertainty. Alternative C densities for four types were taken from Fearnside (1992), i.e., closed moist forest, other closed forest, cerrado woodland, and wetland/mangrove (Table VI.2). In addition, two alternatives were taken from Brown and Lugo (1992) and Kauffman et al. (1994b), i.e., closed moist forest and savannah/grassland (Table VI.2). When no other published datawere available, however, the Olson C estimates were used as default values (see Section VI.D for further considerations).

Published estimates of root/shoot ratios were used to partition phytomass C into aboveground and belowground components (Table VI.3). Further, published results were used to estimate C in litter and CWD. A companion report to Olson et al. (1983) provides soil organic C estimates for all of the Olson vegetation types (Zinke et al. 1984). These values were also applied to the Stone map (Table VI.4).

By these methods, estimates of C density for terrestrial phytomass were determined for each of the vegetation or land-use types (Table VI.4). Nation-wide pools were then calculated by aggregating C pools across the major vegetation or land-use types (Table VI.6).

4. Brazil's Biotic Carbon Flux

Published data were used to calculate flux estimates (Table VI.5). It was assumed that mature vegetation was in an equilibrium or steady state where uptake and release via biological processes were balanced for all pools on a per unit area basis with no net gain or loss of C. There is growing uncertainty, at least for closed moist forest, that this assumption is appropriate. Brown and Lugo (1992) believe that most forests in the Brazilian Amazon, for example, are not in C steady state because of past widespread exploitation. The implications of altering the steady state assumption are addressed in more depth in Section VI.D.6.

Besides the background flux associated with each vegetation and land-use type, changes were accounted for in the area of any of these vegetation types (i.e., annual change from one vegetation type to another land use). Each such land-use change created an important C flux.

Table VI.3. Root/Shoot Ratios and Factors Used in the Brazilian Study

Vegetation and Land-Use Type*	Root/Shoot Ratio	Litter/CWD (in relation to above-ground phytomass C)
Closed tropical moist forest (TMF)	0.2†	0.135☆
Recently degraded TMF		
Secondary forest	0.2‡	0.135■
Degraded forest/mixed agriculture	0.2##	0.135##
Pastureland	1.6¶	0.0††
Other closed forest	0.23§	0.04**
Degraded closed forest		
Agriculture	0.18#	0.0††
Secondary Forest	0.23♠	0.04‡‡
Cerrado woodland	1.6¶	2 MgC/ha§§
Degraded woodland	1.6I	0.0¶¶
Savannah/grassland	1.6♦	0.0‡‡
Degraded savannah (converted to agriculture)	0.18#	0.0††
Wetland/mangrove	0.75▲	0.0††

*Stone et al. (1994).

†Fearnside (1992); Jordan and Escalante (1980).

‡Saldarriaga (1985).

§Cannell (1982) (India).

¶As for shrub/grassland.

#Sanchez et al. (1989).

♠Same as other closed forest.

♦Singh and Joshi (1979); Fiala et al. (1991) (Cuba).

ISame as woodland.

▲Cannell (1982) (mangroves).

☆Salati et al. (1991); Uhl et al. (1988); Uhl and Kauffman (1990).

■Same as closed moist forest.

**Kauffman et al. (1993), Schacht et al. (1988) for caatinga forest.

††Assumption.

‡‡Same as other closed forest.

§§Kauffman et al. (1994b).

¶¶Assumes frequent burning and no litter accumulation.

##Same as secondary forests.

Table VI.4. Carbon Density in Phytomass Components and Soil by Vegetation and Land-Use Type, Brazil*

Vegetation and Land-Use Type	C Density (MgC/ha)				
	Total Phytomass†	Above-ground	Roots	Litter/ CWD‡	Soil§
Closed tropical moist forest (TMF)	137-200¶	114-167	22-33	15-22	104
Recently degraded TMF					
Secondary forest	40	33	7	4	94
Degraded forest/ mixed agriculture	25	21	4	3	94▲
Pastureland	10	4	6	35-52#	95
Other closed forest	60-172	49-140	11-32	2-6	100
Degraded closed forest					
Agriculture	8	7	1	0	75
Secondary Forest	40	32	8	1	90▲
Woodland	22-30	8-12	14-18	2	60
Degraded woodland	20	8	12	0	60
Savannah/grassland	3-9	1-3	2-6	0	60
Degraded grassland (converted to agriculture)	8	7	1	0	54▲
Wetland/mangrove	30-190	17-108	13-81	0	234

*Developed from Tables VI.2 and VI.3

†The sum of the C densities for "Aboveground" and "Roots" may not equate exactly with that for "Total Phytomass" because of rounding.

‡Values are the product of proportion factors in Table VI.3 and the above-ground C densities of Table VI.4.

§Values from Zinke et al. (1984).

¶See Section VI.D. Discussion for consideration of some reports of higher C density values by dos Santos (1987) and Anderson and Spencer (1991).

#Values are area-weighted means for above-ground residual C from remaining snags and logs; in addition, the area-weighted means for remaining dead roots are 10 to 15 MgC/ha; see Methods in text for full explanation.

▲Assumes 10% C loss due to disturbance.

Table VI.5. Total Area, Area Cleared, Flux Parameters per Hectare, and Estimates Used to Compute Net Carbon Balance, Brazil

Vegetation and Land-Use Type	Flux Parameter	Estimate	Source/Basis
Closed tropical moist forest (TMF)	Total Area (X 10^6 ha)	352.2	Stone et al. (1994)
	Area Cleared (X 10^6 ha)	1.38	Fearnside (1992)
	Deforestation/burning factors:		
	% aboveground C to charcoal/yr	3.6	Fearnside (1992)
	% aboveground C released/yr	27.5	Fearnside (1992) Crutzen & Andrae (1990)
	% litter released/yr	95.0	Assumption
	% soil C released/yr	5.0	Cerri et al. (1991) Sanchez et al. (1983)
	Net flux (MgC/ha/yr)	-50.0 to -70.3	
Recently degraded TMF Secondary forest	Total Area (X 10^6 ha)	17.4	Stone et al. (1994)
	Tree growth (MgC/ha/yr)	3.0	Saldarriaga (1985) Brown & Lugo (1990)
	Litter accumulation (MgC/ha/yr)	1.0	Walschburger & von Hildebrand (1991)
	Soil C accumulation (MgC/ha/yr)	1.0	Lugo et al. (1986)
	Net flux (MgC/ha/yr)	+5.0	
	Deforestation/burning factors:		
	Area cleared (X 10^6 ha)	0.35	Fearnside (1992)
	% aboveground C to charcoal/yr	3.6	Same as closed moist forest
	% aboveground C released/yr	60.0	Ewel et al. (1981)
	% litter released/yr	95.0	Same as closed moist forest
	% soil C released/yr	5.0	Same as closed moist forest
	Net flux (MgC/ha/yr)	-28.3	
Degraded forest/ mixed agriculture	Total Area (X 10^6 ha)	19.4	
Pastureland	Total Area (X 10^6 ha)	15.1	Stone et al. (1994)
	Vegetation growth (MgC/ha/yr)	1.0	Fearnside (1992)
	Decomposition/reburning (MgC/ha/yr)	4.2 to 6.1	See text
	% soil C released/yr	0.5	Fearnside (1992) Detwiler (1986) Houghton et al. (1991a) Davidson et al. (1992)
	Net flux (MgC/ha/yr)	-3.2 to -5.1	
Other closed forest	Area (X 10^6 ha)	16.4	Stone et al. (1994)

continued

Table VI.5. (Continued)

Vegetation and land-use type	Flux parameter	Estimate	Source/Basis
Degraded closed forest Agriculture	Area (X 10^6 ha)	99.7	Stone et al. (1994)
	% soil C released/yr	1.0	
	Net flux (MgC/ha/yr)	-0.75	Assumed to be larger than releases from pasture
Secondary forest	Area (X 10^6 ha)	17.6	Stone et al. (1994)
Cerrado woodland	Total Area (X 10^6 ha)	155.6	Stone et al. (1994)
	Deforestation/burning factors:		
	Area cleared (X 10^6 ha)	1.0	Fearnside (1992)
	% aboveground C to charcoal	0.0	Based on assumptions described in text
	% aboveground C released	100.0	
	% root C released	100.0	
	% soil C released	5.0	As for forest
	Net flux (MgC/ha/yr)	-35.0	
Degraded woodland	Area (X 10^6 ha)	33.0	Stone et al. (1994)
Savannah/grassland	Area (X 10^6 ha)	74.0	Stone et al. (1994)
Degraded savannah (converted to agriculture)	Area (X 10^6 ha)	17.9	Stone et al. (1994)
	% soil C release/yr	1.0	Assume to be larger than releases from pasture.
	Net flux (MgC/ha/yr)	-0.56	
Wetland/mangrove	Area (X 10^6 ha)	12.4	Stone et al. (1994)

Table VI.6. Total Carbon Pools in Brazil by Vegetation and Land-Use Types Calculated with a Variety of Carbon Density Values (Tables VI.2 and VI.3)*

	Olson 1983, 1985		Fearnside 1992					Brown & Lugo 1992; Kauffman et al. 1994b							Zinke et al. 1984
Vegetation and Land-use Type	Phytomass (PgC)	%	Below-ground (PgC)	Above-ground (PgC)	Litter/ CWD (PgC)	Phytomass (PgC)	%	Below-ground (PgC)	Above-ground (PgC)	Litter/ CWD (PgC)	Phytomass (PgC)	%	Below-ground (PgC)	Above-ground (PgC)	Litter/ CWD (PgC)	Soil (PgC)
Closed tropical moist forest (TMF)	70.4	86	11.7	58.7	7.9	67.3	83	11.2	56.1	7.6	48.3	81	8.1	40.2	5.4	36.6
Recently degraded TMF																
Secondary forest	0.7	1	0.1	0.6	0.1											1.6
Degraded forest/ mixed agriculture	0.5	1	0.1	0.4	<0.1											1.8
Pastureland	0.1	<1	0.1	<0.1	0.8	0.1	<0.1	0.1	<0.1	0.7	0.1	<0.1	0.1	<0.1	0.5	1.4
Other closed forest	1.0	1	0.2	0.8	<0.1	2.8	3	0.5	2.3	0.1		2				1.6
Degraded closed forest																
Agriculture	0.8	1	0.1	0.7	0.0		1					1				7.5
Secondary forest	0.7	1	0.1	0.6	<0.1		3					1				1.6
Cerrado woodland	4.7	6	2.9	1.8	0.3	3.4	6	2.1	1.3	0.3		8				9.3
Degraded woodland	0.7	1	0.4	0.3	0.0		1					1				2.0
Savannah/grassland	0.5	1	0.3	0.2	0.0		1				0.2	<1	0.1	0.1	0.0	3.3
Degraded savannah (converted to agriculture)	0.1	<1	<0.1	0.1	0.0		<1					<1				1.0
Wetland/mangrove	0.4	<1	0.2	0.2	0.0	2.4	<1	1.1	1.3	0.0		1				2.9
TOTALS	80.8		16.3	64.5	9.2	80.2†		16.2†	64.0†	8.9†	58.3†		12.5†	45.8†	6.4†	71.7

*Vegetation and land-use types after Stone et al. (1994); all columns may not balance because of rounding.

†Totals include values from columns under Olson 1983, 1985 as default values for the blank spaces in respective columns above figures with †.

It was assumed that most of the degraded vegetation types were in a disequilibrium state (i.e., either accumulating or releasing C), so data were sought to quantify the C flux. Information for degraded woodlands, however, was insufficient to form a basis for any kind of flux estimates. This vegetation type, however, only occupies 4% of the area of the nation (Table VI.1).

There was also insufficient information available to quantify flux for the areas of degraded closed forest listed as secondary forest, 17.6 X 10^6 ha (Table VI.1). This area is located primarily along the Atlantic coast of Brazil where human population densities are high. For this reason, it is likely that these secondary forests experience fairly intensive use to supply wood for fuel, housing construction, and other purposes. Therefore, it is unlikely that these secondary forests are experiencing recovery and regrowth as is the case in the less-populated Amazon basin. In summary, the secondary forests of the former Atlantic forest region could be net sources of C to the atmosphere, but data were not found to support or refute this idea.

Much the same can be said for the area that was designated as degraded forest with mixed agriculture in the TMF zone of eastern Amazonia. This area, in the states of Para and Maranhao, has been settled for a long time. No information was available to estimate C fluxes for this vegetation class which forms a very heterogeneous landscape of different land uses.

Major fluxes in Brazil's C budget are released to the atmosphere resulting from land-use change. Three types of land-use change were included in the analysis: conversion of closed moist forest to pasture or low intensity shifting cultivation, conversion of secondary forest to pasture or low intensity shifting cultivation, and conversion of cerrado woodlands to intensive agriculture (e.g. for soybean). In 1990, 1.38 X 10^6 ha of closed forest

were cleared in Brazil (INPE 1992) with an additional 1.0 X 10^6 ha of cerrado woodland (Fearnside 1992).

No nationwide estimates of clearing of secondary forest were available, although it seems reasonable that some clearing of this forest type must occur. Only regional studies have been published. Skole et al. (1994) reported that in an area of Rondonia, clearing of secondary vegetation was an important source of new agricultural land. From 1988 to 1989, the area of secondary forest cleared was about 70% as large as the area of mature forest cleared. However, Moran et al. (1994) cite data from Para that indicate abandonment of pastures and agricultural lands was 1.5 to 2.5 times as large as the rate of new clearing. The rapid expansion of secondary forest in their study area implies that relatively little was being cleared. Hecht (1993) and Fearnside (1989) also seem to imply that most pastures are created from mature forest and that abandoned areas are usually left to secondary vegetation. These differing reports make it difficult to decide on an appropriate factor for secondary forest clearing. Therefore, it was assumed, more or less arbitrarily, that the clearing rate for secondary forests was 25% that of mature forests, or about 0.35 X 10^6 for 1990 (Table VI.5).

Releases of C from deforestation were calculated by multiplying C density by estimates of combustion efficiency (deforestation/ burning factors, Table VI.5). The combustion efficiency, the proportion of aboveground phytomass C released to the atmosphere at the time of deforestation, for closed moist forest (27.5% from Fearnside 1992) and secondary forest (60% derived from Ewel et al. 1981) reflect the assumption that these areas are cleared for pastureland or low intensity shifting cultivation. The factor for cerrado woodlands (100%) is based on the assumptions that (1) these areas are cleared for types of intensive agriculture (e.g., soybean cultivation) requiring they be completely cleared and (2) the vegetation at the time of burning is very dry because of the

arid environment. A factor was also included for release of soil C due to the disturbance caused by forest clearing and burning (5% of soil C in the upper 1 m; Table VI.5).

The calculation of C release from maintaining pasturelands, via decomposition and reburning of remaining residual forest phytomass, is more complicated. The initial burning of the forest releases only a little less than 30% of aboveground C and no belowground root C (given the assumptions reflected in Table VI.5 that burning does not consume root phytomass). This leaves a significant amount of residual C that must be accounted for in the overall flux estimates.

As a working base, the pastureland management scenario described by Fearnside (1992) was adopted. This is a typical management scenario that includes three reburnings over a period of 10 years. Bacterial decomposition and termite activity also release C under this scenario which results in the consumption of all of the residual C by the end of the assumed 10 year period. A mean was calculated for the residual aboveground C density in all pasturelands by (1) using the charcoal and combustion factors in Table VI.5; (2) dividing the total pastureland area into 10 equal sized age classes; and (3) assuming linear rate of release over 10 years. Further, a mean residual root C was calculated in a similar manner. The means for residual aboveground C density (i.e., CWD) ranged from 35 to 52 MgC/ha with a range of 10 to 15 MgC/ha in residual root C (Table VI.4).

Working with proportions of C released in initial and reburns presented by Fearnside (1992), it was calculated that about 76% of the residual aboveground C would be released by decomposition; the remainder (24%) would be released by reburning. It was assumed that all of the residual belowground phytomass would be decomposed. With a linear decomposition rate over 10 years, this calculation gave an annual decomposition release of 3-5 MgC/ha/yr

aboveground and about 1 MgC/ha/yr belowground. The C releases from reburning were estimated on an area-wide basis because it does not occur on every ha annually. The total annual area-wide release from reburning was calculated as a proportion of the total area-wide decomposition release, i.e., about 30% (0.24/0.76), of the total area-wide decomposition release. Pasturelands also gradually accumulate C both in roots and in the aboveground biomass of invading woody vegetation (Table VI.5).

C. Results

Key results for the Brazil case study are in two parts, C pools and C flux. The nominal base year for all results is 1990.

1. Carbon Pools

The total phytomass C pool for all ecosystems was 81 PgC, 80 PgC, and 58 PgC with the Olson, Fearnside, and Brown and Lugo/Kauffman et al. C estimates, respectively (Table VI.6). In all three cases, closed moist forest predominated with 86%, 83% and 81% of the total phytomass C, respectively. By contrast, the other geographically important ecosystems together accounted for only 14-19% of phytomass C. Differences in total pool size were due primarily to differences in estimates of C in closed moist forest (Table VI.6). Nationwide, the closed moist forest phytomass C pool was 70 PgC, 67 PgC, and 48 PgC based on the Olson, Fearnside, and Brown and Lugo/Kauffman et al. C density estimates, respectively.

The litter and CWD C pool was an order of magnitude smaller than the phytomass pool. The range was from less than 6 PgC to about 9 PgC (Table VI.6). Most of this pool was also contained in the closed moist forest (5-8 PgC). The total estimated pool size for soil C was 72 PgC (Zinke et al. 1984) (Table VI.6). Combined,

the phytomass, litter plus CWD, and soil pools ranged from 136 to 162 PgC, 55-62% of which was belowground. Compared to the total C pool for the nation, the total closed moist forest pool represented 66-71% (Table VI.6).

2. Carbon Flux

Because the magnitude of C emissions was largely dependent on C density and pool sizes, there was also a range of results for the net C flux of the nation as a whole (Table VI.7). This resulted from both biological activity and land-use changes. The range was from a net emission of 174 TgC/yr to 233 TgC/yr. The difference was caused mostly by differing estimates in the C density of closed moist forest which resulted in different flux rates from deforestation and burning. Combustion efficiency values, however, also have a significant influence (see Section VI.D.4).

As expected, direct C emissions from clearing and burning closed moist forest were large, 69-97 TgC/yr (Table VI.7 and further consideration in Section VI.D.1). However, emissions from decomposition and reburning of existing pasturelands were nearly as large, 62-93 TgC/yr. Two other classes of C releases resulted from (1) clearing and burning cerrado woodlands, 27-35 TgC/yr and (2) releasing soil C by intensive agriculture: 75 and 10 TgC/yr from converted closed forest and converted grassland, respectively (Table VI.7).

Net changes in the total nationwide pool sizes of the C budget model varied. For all three of the C density matrixes, the litter/CWD pool increased by 70-90 TgC/yr (Figures VI.3-5). This was largely the result of large transfers of 140-205 TgC/yr from the vegetation C pool due to deforestation. The vegetation C

Table VI.7. Net Carbon Flux by Vegetation and Land-Use Types, Brazil

Vegetation and Land-Use Type	Net Flux* (TgC/yr)
Closed tropical moist forest (TMF)	-97, -93, -69
Recently degraded TMF	
Secondary forest	+77
Degraded forest/mixed agriculture	ND
Pastureland	-93, -89, -62
Other closed forest	ND
Degraded closed forest	
Agriculture	-75
Secondary forest	ND
Cerrado woodland	-35, -27, -35
Degraded woodland	ND
Savannah/grassland	ND
Degraded savannah (converted to agriculture)	-10
Wetland/mangrove	ND
Total Net Flux	-233, -217, -174

*Flux is uptake minus release. A plus sign indicates net C uptake by vegetation or human activity. A minus sign indicates net C release. Multiple values result from the three mixes of C density values used. From left to right, the results in the table were derived from the Olson (1983, 1985), Fearnside (1992), and Brown and Lugo (1992)/Kauffman et al. (1994b) C density mixes. Where no net flux is given, the type is assumed to be in C steady state or available information was insufficient to estimate flux. A row with only one value implies that the value applies to calculations for all three sources.

ND No datum.

pool, therefore, decreased 240 and 230 TgC/yr for the Olson and Fearnside C density values, respectively, and 160 TgC/yr for the Brown and Lugo/Kauffman et al. C densities. The lesser estimate of C in closed moist forest of the latter produced a smaller C transfer from deforestation. The soil pool lost 80 TgC/yr because of soil disturbance associated with deforestation and ongoing soil C loss from intensive cultivation.

Total gross C input to the system was 100 TgC/yr of which 60 TgC/yr was vegetation growth and 40 TgC/yr was added to litter-CWD and soil pools in secondary forests (Figures VI.3-5). Total C releases were 120-150 TgC/yr from deforestation/burning and 150-180 TgC/yr from decomposition (Figures VI.3-5). Most C released from burning derived from aboveground vegetation, but a significant amount also came from litter and CWD, including reburning of residual logs on pasturelands.

D. Discussion

Brazil's large geographic size and predominantly tropical climate combine to make a vast vegetative C pool. The pool ranges from 58-81 PgC in live aboveground vegetation and roots (Table VI.6). The size of the vegetation C pool estimated here for Brazil represents approximately 10% of the total global vegetation pool of 560-830 PgC (Schneider 1989), or 16-22% of global forest vegetation pool (Dixon et al. 1994). Brazil's soil C pool (71.7 TgC, Table VI.6) is 4-7% of the global soil C pool of 1100-1700 PgC (Dixon and Turner 1991).

By far the largest portion of the vegetation pool in Brazil is contained in the closed moist forest; the estimates were 81-86% of the total vegetation pool (Table VI.6). Future attempts to refine this type of analysis, therefore, should focus on the closed moist forest. There is undoubtedly variation in the

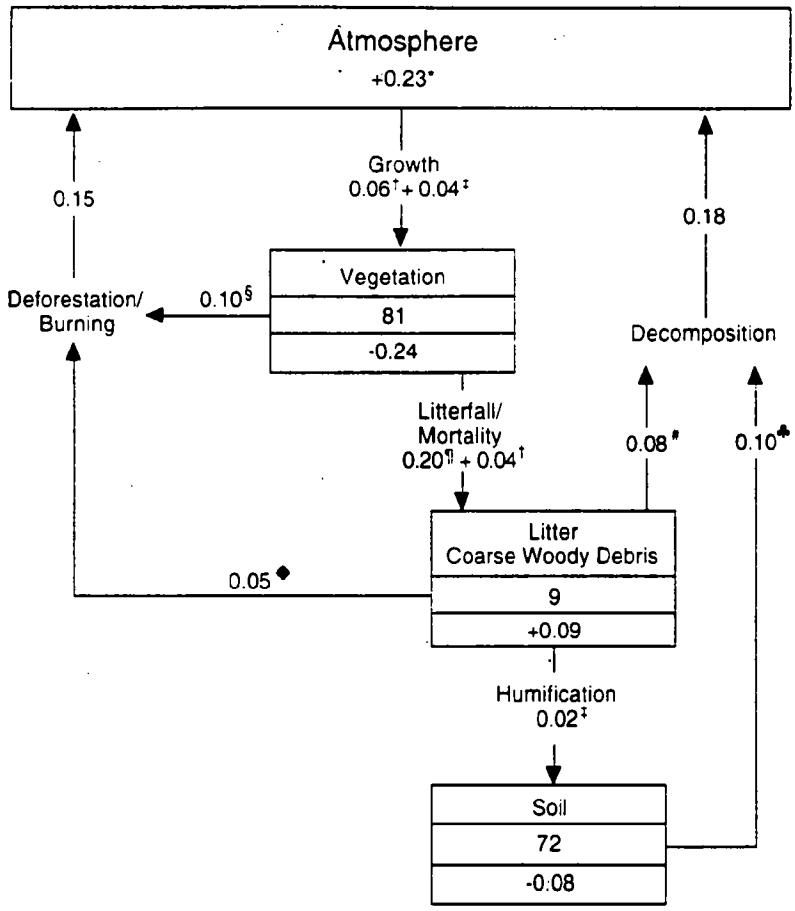


Figure VI.3 Annual net carbon balance for Brazil using the Olson (1983, 1985) carbon density values. Boxes are pools (Table VI.6), arrows are fluxes, and all units are PgC. The upper number in each box is the pool size. The lower number is the net annual change in the pool size.

* The 0.23 PgC represents a net gain of C to the atmosphere (shown as an emission of 233 TgC in Table VI.7) as a result of summing the emissions and uptake in PgC from closed moist forest, -0.097; secondary forest, +0.077; pastureland, -0.093; degraded closed forest, -0.075; cerrado woodland, -0.035; and degraded savannah, -0.010.

† The uptake of 0.06 PgC is 0.05 PgC from secondary forest plus 0.01 PgC from pastures

‡ Litterfall accumulation is 0.04 PgC primarily in secondary forests which then contributes 0.02 PgC to the litter C pool and ultimately 0.02 PgC to the soil C pool through humification.

§ The emission of 0.10 PgC is the sum of 0.06 PgC from deforestation and burning (including removals of harvested logs) in the closed moist forest; 0.01 PgC from burning in secondary forests; and 0.03 PgC from burning in the cerrado woodlands in preparation for agriculture crops.

¶ The 0.20 PgC consists of logs and other CWD left aboveground after deforestation.

Decomposition emissions of 0.08 PgC from litter and CWD consists primarily from decay of logs and roots in patsures and roots in cleared cerrado woodlands.

♣ Decomposition emissions of 0.10 PgC from soils is the result of human disturbances in six vegetation types: closed moist forests, 0.01; secondary forests < 0.01; pastureland, 0.01; degraded closed forest, 0.07; cerrado woodlands, < 0.01; and degraded savannah, 0.01.

♦ Burning of litter and CWD results in emissions of 0.05 PgC which consists of closed moist forest, 0.03 secondary forests, < 0.01; pastureland, 0.02; and cerrado woodlands, < 0.01.

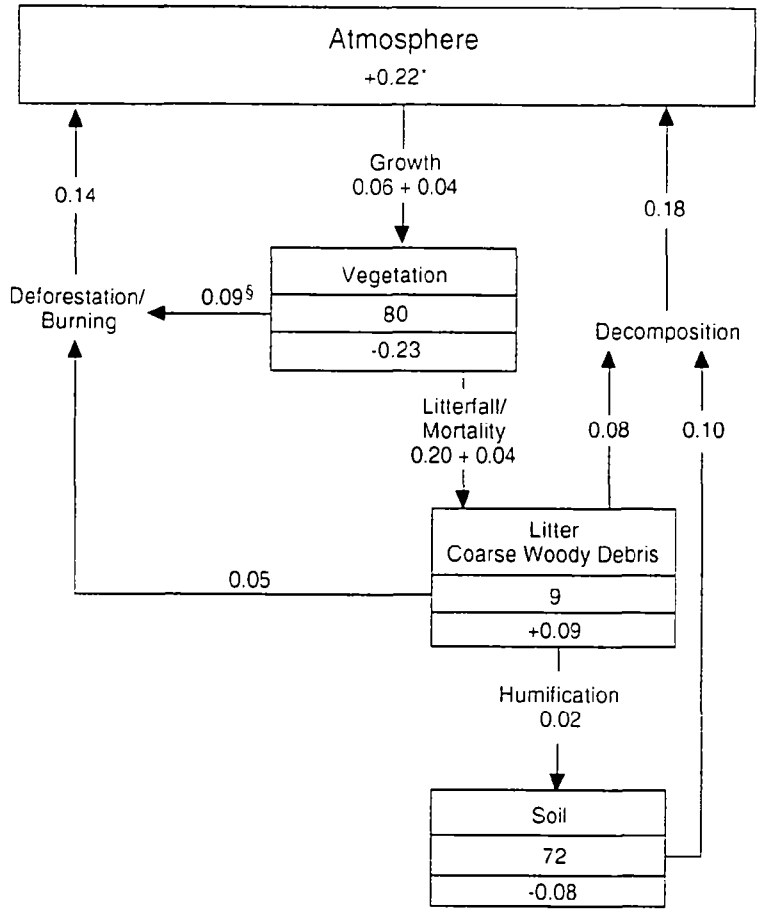


Figure VI.4. Annual net C balance for Brazil during 1990 using the Fearnside (1992) carbon density values. Boxes are pools, arrows are net fluxes, and all units are PgC. The upper number in each box is the pool size (Table VI.6), and the lower number is the net annual change in the pool size.

* Following from the footnote above, the net gain of C to the atmosphere (shown as an emission of 217 Tg in Table VI.7) is 0.01 PgC less than the value in Figure VI.3.

§ The C density value of Fearnside (1992) for closed moist forest of 191 MgC/ha (Table VI.2) is lower than the Olson (1983, 1985) value of 200 MgC/ha. Similarly, for the cerrado woodlands, Fearnside's C density value is 22 Mg/ha compared to Olson's value at 30 MgC/ha. These differences cause the emission of C from deforestation and burning in both vegetation types to be 0.01 PgC less than the value in Figure VI.3.

Other footnotes for the net flux arrows in Figure VI.3 also apply in this figure.

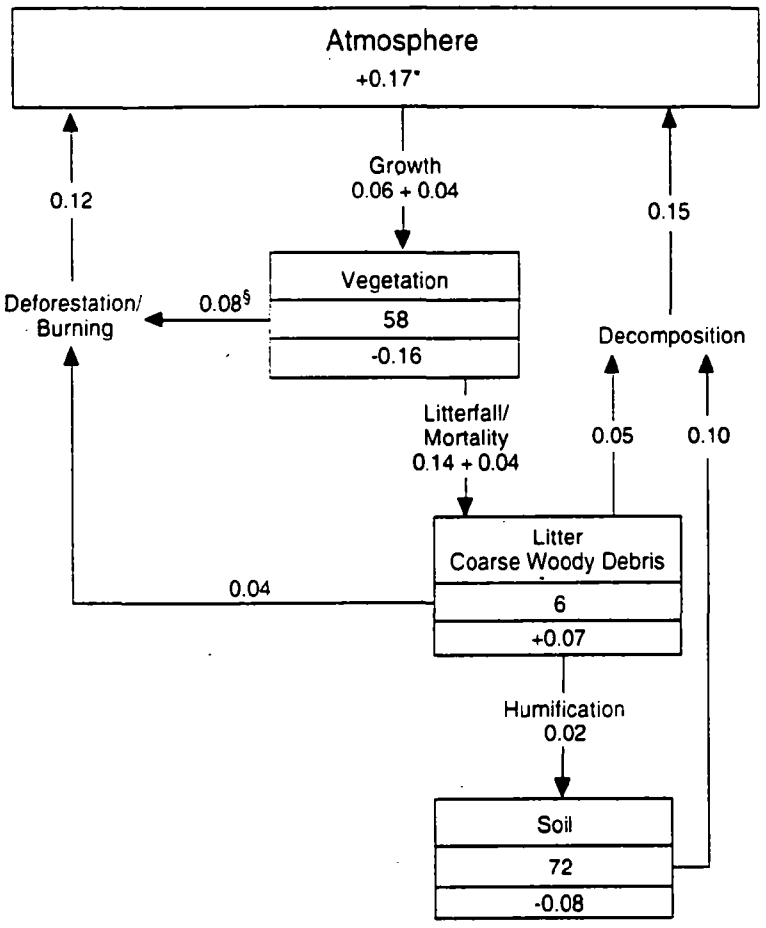


Figure VI.5. Annual net C balance for Brazil during 1990 using the Brown and Lugo (1992) carbon density values. Boxes are pools, arrows are net fluxes, and all units are PgC. The upper number in each box is the pool size (Table VI.6), and the lower number is the net annual change in the pool size.

* Following from the footnote above, the net change of C to the atmosphere (shown as a release of 174 TgC in Table VI.7) is a 0.06 PgC difference than the value in Figure VI.3 for the uptake of C by terrestrial ecosystems in Brazil.

§ The C density value of Brown and Lugo (1992) for closed moist forest of 137 MgC/ha (Table VI.2) is lower than the Olson (1983, 1985) value of 200 MgC/ha. This causes the emission of C from deforestation and burning to be 0.02 PgC less than the value in Figure VI.3. Also the same lower C density value used in this figure results in less emissions from burning (0.04 vs 0.05 PgC) and decomposition (0.05 vs 0.08 PgC) of litter/CWD than in Figure VI.3.

Other footnotes for the net flux arrows in Figure VI.3 also apply in this figure.

phytomass and C content of these forests that is not adequately reflected in the analysis and which is an important source of uncertainty. For example, dos Santos (1987) reported phytomass densities for eastern Amazonia ranging from 266 to 915 ton/ha (i.e., about 133-458 MgC/ha). Similarly, Anderson and Spencer (1991) reported a range of 185-513 ton/ha (i.e., about 93-257 MgC/ha). The lower end of these ranges are comparable to the values used in this analysis (Table VI.4). The values apply to southeastern and southern portions of the Brazilian closed moist forest where the majority of the recent deforestation has occurred (Fearnside 1993). The high-end values would not affect the estimates of C flux for the vegetation type. However, the higher values, if shown to be representative of a large portion of the Brazilian closed moist forest, would increase the C pool estimate. This is an important topic for refinement in future analyses of the C budget for Brazilian forests.

Based upon the literature, the C flux estimates of this study for all major vegetation and land-use types in Brazil were the first that reached beyond the Amazon region. Thus the estimated 1990 net C flux of the vegetation and land-use types for the nation as a whole ranged between -174 and -233 TgC/yr (Table VI.7). The study demonstrated the dominance of the Amazonian region in the C dynamics of the nation. It contains the largest C pool (closed moist forest), the two largest release flux rates (deforestation at 69-97 TgC/yr and decomposition of residual wood on pasture-lands at 62-93 TgC/yr), and the largest uptake flux (growth of secondary forests at 77 TgC/yr [Table VI.7 and possibly by the mature TMF at 176 TgC/yr as suggested in Section VI.D.6]). Characterization of Brazil's C flux could be largely accomplished by focusing on the Amazonia region. Improved information on C accumulation by both mature and secondary forests and the fate of C during and after deforestation would be useful in future studies.

The largest biotic C emissions from Brazil are driven by human factors related to land-use change. These include a developing economy, an expanding population, prevalent poverty, land speculation, and government tax-breaks or subsidies to large land owners in conjunction with the existence of a large resource-rich region of undeveloped land in the Amazon basin (Hecht 1992; Schmink and Wood 1992). Gross C emissions to the atmosphere resulting from current and past land-use change may be as high as 300 TgC/yr (Table VI.7). In addition to this possible contribution to greenhouse gas emissions, the environmental degradation caused by deforestation and the threats to biological diversity that it entails are well known (Randall 1991). Throughout the early 1990s, Brazilian deforestation rates have been declining, but this may be mostly due to the nation's current economic crisis. Once Brazil's economy recovers, deforestation rates are expected to rise again (Fearnside 1992).

1. Comparisons to Other Studies

The most intensive analysis of Brazilian C dynamics, heavily cited here, was performed by Fearnside (1992) for the Amazon basin. That study determined that clearing 1.38 X 10^6 ha/yr of mature forest in the period 1989-1990 was responsible for the release of approximately 270 $TgCO_2$-C/yr. That study, however, was focused on C emissions and did not include C uptake by secondary forests. It, therefore, estimated C release rather than net C balance. There is also a difference in accounting for the fate of C released from cleared forest. Fearnside's approach was to account in the base year for all C that would ultimately be released due to deforestation. This approach, sometimes called the committed C approach to estimating emissions, attributes all C release to the year in which the deforestation occurs. In the nationwide analysis for Brazil that is presented here, the method was to develop an estimate of the annual C flux

that focused on the actual C released from deforestation in 1990 and also accounted for release of residual C from decomposition and reburning of pastures that resulted from previous deforestation.

Another recent study (Subak et al. 1993) estimated that net biotic CO_2-C releases from Brazil were 213 X 10^6 MgC/yr, which is within the range of our estimates in this analysis. Although this study included C uptake by vegetation, it only estimated it for plantations. By not including non-commercial secondary forests, Subak et al. (1993) may have underestimated C uptake.

2. Base Map Used for Study

The map used here by Stone et al. (1994) is very current and was derived from a continental-scale data set. AVHRR-derived vegetation maps, however, are subject to their own disadvantages (Townshend et al. 1991). Even a resolution of 1.1 km can be rather coarse for vegetation mapping, particularly in areas of heterogeneous vegetation cover. Mixed pixels can produce signals that do not accurately depict the actual vegetation present. Another problem inherent in all broad-scale maps is that it is impossible to fully verify the accuracy of the various types of vegetation and land use and of the map itself. This is due simply to the size of the area being mapped; it is much too large to be directly ground-truthed. The Stone group addressed this problem by conducting a series of accuracy assessments and ground study comparisons. They examined the variation in information sources used to develop classifications within the map, and they compared other estimates of the areal extent of land-cover types to their findings. In addition, they compared land-cover type assignments in a widely distributed set of sites to external land-cover descriptions from field studies. They concluded that the vegetation types covering 85% of the whole map of South

America were correctly assigned 90% of the time. They also determined that the vegetation types for Brazil were among the most reliable for the entire continent (Stone et al. 1994).

Although the resolution of the Stone map may have some disadvantages in a strictly cartographic sense, it seemed very suitable for estimating major C pools over a very large area. More detailed vegetation maps of Brazil with much finer stratification of vegetation types are available, for example, the UNESCO (1980) and IBGE/IBDF (1993) maps. The usefulness of these maps for this Brazil study, however, was limited by the availability of C density data for the more numerous vegetation types they contain. Lack of C density data for many vegetation types would require some amount of aggregation which would result in a loss of resolution. A wider sampling of C densities for terrestrial ecosystems in Brazil is an important research need (see Section VIII.D).

In another recent study using satellite technology, Skole and Tucker (1993) used a combination of Landsat TM and MSS imagery to estimate the amount of deforestation in the Amazon Basin of Brazil between 1978 and 1988. With this methodology, the authors indicate that deforestation is about 50% less than estimates made with coarser resolution AVHRR satellite data for the southern Amazon Basin of Brazil. Across the whole Brazilian Amazon Basin, the authors compared the area deforested in 1978 with that in 1988. A breakdown of the increase in deforested area into estimates of current land uses such as secondary forests or pastureland was not indicated. While the improved precision of deforestation estimates by Skole and Tucker (1993) is important to note, the Brazil analysis described in the current report required estimates for major vegetation and land use types within the deforested areas throughout the nation for 1990. Thus it was felt that the recent 1.1 km resolution map by Stone et al. (1994) was appropriate for the sub-continental and nationwide analysis

as required here for Brazil. Further, a comparative advantage of the AVHRR-based map is that the use of training sets enabled the Stone group to identify the spectral signature of secondary forests. In addition, this approach recognizes that deforestation occurred in decades prior to 1978 and continued after 1988.

3. The Role of Secondary Forests: A Sensitivity Analysis

At least two recently published articles have commented on the widespread occurrence of secondary forests in Amazonia (Skole et al. 1994; Moran et al. 1994). However, there is no reliable estimate for the area of these forests in Brazil. This analysis used an area of 15.1 X 10^6 ha of secondary forest in Amazonia as the major part of the total of 17.4 X 10^6 ha (see Section VI.B.2) by partitioning the very heterogeneous degraded TMF vegetation class defined by Stone et al. (1994). An important factor in this partitioning was weighting the areas of secondary forest and pastureland. Based on several references from the literature, these two vegetation classes were weighted at 50% each, but there were also higher and lower published values (Schroeder and Winjum 1995a, 1995b).

To evaluate the importance of this uncertainty on total C emissions from Brazil, a sensitivity analysis was conducted by altering the areas of secondary forest and pastureland. The secondary forest/pasture ratio by was changed ±20% to correspond to a lower estimate reported by Skole et al. (1994) and a higher estimate derived from Moran et al. (1994). This resulted in large changes in C releases (Table VI.8). Partitioning up to 70% of the area in question to secondary forest resulted in a decrease in total C emissions of about 30%. When 30% of the area was partitioned to secondary forest, total C emissions rose by about 30%. This is equivalent to a change of ±56-69 MgC/yr.

Secondary forests play an important role in Brazil's C budget because they are very active in fixing and storing atmospheric C. However, there is much uncertainty about specifically how large that role is. A nationwide inventory of the area and age class distribution of secondary forests would help to resolve this uncertainty.

The results also suggest that tropical secondary forests may be more important in the global C cycle than previously realized. Current estimates of the global C budget show an imbalance of 1.1 PgC/yr; i.e., known C sources exceed known and modeled sources (Dixon et al. 1994). There has been much discussion and debate about the fate of this "missing" C. Perhaps it is possible that tropical secondary forests are a larger C sink than they are accounted for in current global C budgets.

4. Changes in Combustion Efficiency

An important variable in this analysis was the combustion efficiency of deforestation burning. The combustion efficiency of 27.5% used in this analysis (Table VI.5) has been observed in actual fires in the Amazon (Fearnside 1992), but there likely is wide variation that depends on an array of factors (Molion submitted). To test the importance of variation in combustion efficiency, a flux calculation was made with a substituted value of 50%. The result was that total net C releases to the atmosphere were actually reduced by 5-6 TgC/yr. A higher combustion efficiency releases more C during the initial burn, and results in a smaller pool of residual C on pasturelands. Therefore, pasturelands release far less C from reburning and decomposition than when the initial combustion efficiency is lower.

Table VI.8. Sensitivity Analysis of the Effect of the Area of Secondary Forest on Brazil's Net C Balance*

Secondary forest area (X 10^6 ha)	C Density Matrix (TgC/yr)		
	Olson (1983 & 1985)	Fearnside (1992)	Brown & Lugo (1992)
11.4	-302	-283	-228
17.4	-233	-217	-174
23.5	-166	-151	-118

*Minus signs indicate releases to the atmosphere. Areas of secondary forests represent alternative partitioning of 30.1 X 10^6 ha of the degraded TMF vegetation class in Amazonia between secondary forests and pastureland (i.e., proportions are .7, .5, and .3 as explained in Section VI.D.3).

In this example, decreased releases of C from pasturelands were slightly greater than increased releases during the initial burn. Although this can have some impact on Brazil's annual C balance, the long-term effect on total emissions to the atmosphere is unchanged. The same amount of C will be released as a result of deforestation, but the passage of time may vary.

5. Wood Products and Fossil Fuels

An important C flux not represented in the conceptual model (Figure VI.2) is release resulting from commercial timber harvesting. Some timber harvesting in Brazil is part of the deforestation process (Westoby 1989). Road construction and selective logging establish access to the forest which can then be subject to agricultural colonization (Cottle et al. 1990; Fearnside 1989; Mather 1990). This analysis, therefore, distinguished between timber harvest that may be associated with deforestation processes and timber harvest in managed plantations. It was assumed that C fluxes associated with the former are accounted for in the net flux for deforestation in the closed TMF, i.e., -50.0 to -70.3 MgC/ha/yr (Table VI.5). Harvesting plantations is accounted for separately using the following assumptions. Brazil provides 60% of its domestic industrial wood needs from 7 X 10^6 ha of tree plantations (Mather 1990). Timber harvesting from these managed plantations represents a process that is separate from and in addition to what is normally thought of as deforestation. In 1990 about 72.0 X 10^6 m^3 of the total harvest in Brazil was in industrial roundwood used for fuel, sawnwood, panels, and paper (WRI 1992). Brazil's timber exports are insignificant (< 1% of total harvest) (WRI 1992). Thus 60% of the total harvest of 72 X 10^6 m^3 or 43 X 10^6 m^3 comes from managed plantations. This volume of wood harvested can be converted to C released by making two additional assumptions: (1) 1 m^3 of wood is equivalent to 0.26 MgC/m^3 (i.e., an average

wood density of 0.52 Mg/m^3 X 0.5 MgC/Mg wood) (Marland 1988; Sedjo 1989) and (2) a unit of stemwood phytomass is associated with a total 1.59 units of whole tree phytomass which includes not only bole but also branches, leaves, and roots (Marland 1988; Sedjo 1989). Multiplying all of these factors together produces an estimate of an additional 18 TgC/yr released from timber harvesting of plantations (Table VI.9). This is an estimate of gross release; C uptake by plantations is included with secondary forests. Truly sustained yield plantation management could fully balance C release from harvest with C uptake by regrowth. Release of 18 TgC/yr is comparable to about 8-10% of gross C releases from land-use change and intensive agriculture (Table VI.9 and Figures VI.3-5).

A small amount of C is stored annually in the harvested wood manufactured into durable-wood products. WRI (1992) reported that for 1990 about 21 X 10^6 m^3 of Brazil's wood harvest was used in this manner. Converting this volume to its approximate weight in C (i.e., 1 m^3 = 0.26 tC from above) indicates that about 5.4 TgC was newly stored in durable-wood products in 1990. However, for such products produced in previous years, there is some level of decomposition which releases C. It is assumed here that the annual decomposition emissions of C is about half that of newly produced so the net gain in 1990 was approximately 3 TgC (Table VI.9).

In addition to C released to the atmosphere from biotic sources and timber harvest, there are also releases from burning fossil fuels. Brazil released approximately 50 TgC from fossil fuel usage in 1987 (Graca and Ketoff 1991; Subak et al. 1993). In addition, 3 TgC was emitted annually in the late 1980's from the manufacture of cement (Subak et al. 1993). Combined, these emissions contribute about 18-22% of the total net C flux from Brazil (Table VI.9).

Table VI.9. Total Net Annual Carbon Flux from Brazil, All Sources

Sources	Net Annual Flux* (TgC/yr)
Biotic sources (Table VI.7)	-174 to -233
Timber harvest†	-18
Fossil fuels‡	-50
Cement§	-3
Durable-wood products¶	+3
Total Net Flux	-242 to -301
Potential flux mature TMF#	+176
Net potential flux	-66 to -125

*Flux is uptake minus release. A plus sign indicates net terrestrial C uptake. A minus sign indicates net C release.

†Emissions from plantation harvests as developed in Discussion (section VI.D.5) from Mather (1990) and WRI (1992).

‡Graca and Ketoff (1991); Subak et al. (1993).

§Subak et al. (1993).

¶Accounts for that portion of Brazil's wood harvest manufactured into durable-wood products (see Section VI.D.5).

#Potential value for mature TMF if uptake by vegetation is 1 MgC/ha/yr for half the area (Lugo and Brown 1992), i.e., 176.1 X 10^6 ha (see Table VI.1 and detailed consideration [Section VI.D.6]).

Overall, net annual C emissions from all known sources in 1990 were estimated to range from 242 to 301 TgC/yr (Table VI.9). Net annual global emissions from all sources are about 7 PgC/yr (Sundquist 1993). This means that Brazil's contribution may represent 3-4% of the total. With more definitive data on the potential C uptake by mature tropical moist forests, the nation's contribution might be closer to 1-2% (Table VI.9 and next discussion, Section VI.D.6).

6. Unquantified Flux Processes

Although the major components of the biotic C budget of Brazil are CO_2 uptake in terrestrial ecosystems and emissions by land-use changes, other processes are ongoing which may affect net C balance. At least two are possible: C uptake by mature forests and river transport of C to the ocean. These other processes are potentially important, but detailed data are unavailable or limited in both cases.

Undisturbed tropical mature forests not undergoing land-use change have often been assumed to be in C equilibrium or steady state with no net C gain or loss. However, there may be reason to question this steady state assumption. Lugo and Brown (1992) make the case that the TEC and TEC accumulation rates of tropical forests change over time as a result of past disturbance by people and natural catastrophe. They point out that the Earth's total biotic C pool (560 PgC) is currently considerably smaller than the total pool size possible (900 PgC) for interglacial optimal climatic conditions estimated by Faure (1990). Lugo and Brown (1992) suggest that this means the current biota could store additional C and still be within the estimated optimal storage capacity. They further cite plot-level field data from Venezuela and Puerto Rico that show mature forests accumulating C at rates of 1-2 MgC/ha/yr. In addition, an eddy correlation

study by Fan et al. (1990) estimated that a mature closed forest near Manaus in Brazil had a net C uptake of 2.2 Mg/ha/yr.

Brazil has such a huge area of mature forest in the Amazon region (i.e., > 350 X 10^6 ha, Table VI.1) that the slightest increase in phytomass per ha would result in very significant amounts of C accumulation. Data are limited that quantify such increases region-wide (Molion submitted), but as noted earlier, Lugo and Brown (1992) suggest that possibly half of the mature tropical forests of Brazil could average 1.0 MgC/ha/yr in net uptake. The range may be from as little as 0.25 Mg/ha/yr to as high as 1.75 Mg/ha/yr. Thus a simple matrix of these values indicate the potential C uptake of the mature tropical moist forests of Brazil:

C Uptake (Mg/ha/yr)	Mature TMF (X 10^6 ha) Half 176	Total (Table VI.1) 352
0.25	44	99
1.00	176	352
1.75	308	616

The uncertainly related to this topic clearly indicates that additional research on this potentially significant flux is very important. Not only would more definitive data aid in balancing the global C budget, but they would greatly improve the calculations for the C dynamics of Brazil as well. To illustrate, using an uptake value of 176 TgC/yr for half of Brazil's mature TMF would indicate that the net biotic flux of Brazil is nearly in balance (Table VI.7).

Globally, most C is cycled among three major reservoirs: the atmosphere, the terrestrial biosphere, and the oceans (Holmen 1992). Out analysis on Brazil largely focused on the C exchanged between the first two, although some C is exchanged between the latter two as well. Carbon in water draining from the terrestrial biosphere is transported by rivers to the oceans. Globally, this flux is estimated to be 540 TgC annually, and for

the rivers of the humid tropics the estimate is 250 TgC/yr (Meybeck 1993).

The vast size of the Amazon River makes river transport of C a potentially important flux in Brazil's C budget. The Amazon transports 68 TgC/yr to the ocean in various forms (Kempe 1988). The fate of this carbon, however, is not completely understood. Some is oxidized and returns to the atmosphere either directly from rivers or estuaries or after entering the ocean. By either route, this C is accounted for in the Brazil C budget by the net change approach used for computing release and uptake. The C not oxidized goes into long-term storage in the sediments of lakes, river beds, and the ocean bottom. Over time in river basins such as the Amazon, some riverine meanders develop into cutoff loops that become large C pools. The total C pool for cutoff loops in the Brazilian Amazon basin is unquantified, but if such data becomes available it should be considered in later analyses (L.C.B. Molion, Universidade Federal de Alagoas, Brazil, pers. comm., 1994). For river transport of C worldwide, about 10% is deposited into lakes (Meybeck 1993).

It is the ocean sink that remains to be accounted for in Brazil's C budget. Currently only 6% of the total C transported by the Amazon is known to be deposited on the continental shelf near the river mouth (Showers and Angle 1986). It is estimated that this known flux is about 3 TgC/yr (68 TgC/yr X 6% X [66%, the portion of the Amazon basin in Brazil]). The fate of the remaining Amazon-transported C is unknown.

7. Forest Management for CO_2 Mitigation

Brazil appears to have significant potential to expand the management of its forest resources for C storage and other benefits. By these means, the nation's forest C sink would be

increased, aiding global CO_2 mitigation. Prospects are particularly attractive in the tropical moist forest which occupies slightly over half of Brazil. The same environment that favors vigorous and rich growth in mature forests will also (in theory) produce rapid growth rates in managed forests on deforested lands. In terms of aboveground C uptake, rates reported for forest areas in or similar to the Brazilian Amazon region show the higher potential for managed forests and plantations:

Land use	MgC/ha/yr	References
Pastureland	1	Fearnside 1992 and Table VI.5
Secondary forest		
Unmanaged	2-5	Saldarriaga 1985; Brown & Lugo 1990
Managed	4-20	Brown & Lugo 1990
Plantations	4-25	Brown et al. 1986; Postel & Heise 1988

As of 1990, the Brazilian Amazon had considerable land area that was under producing. Estimates are that in 1990 there was a total of 51.9 X 10^6 ha of recently degraded tropical moist forest divided into secondary forests at 17.4 X 10^6 ha, degraded forest/mixed agriculture at 19.4 X 10^6 ha, and pasturelands at 15.1 X 10^6 ha (Table VI.1). Productivity on these lands could be greatly increased if significant portions were placed under management to grow new secondary forests and plantations or to keep losses in existing stands to a minimum.

The amount of managed secondary forests reported for Brazil is only a few thousand hectares (WRI 1992). Most of the 51.9 X 10^6 ha was originally cleared for pastureland or slash-and-burn agriculture, became degraded, and was left to become unmanaged secondary forest (Fearnside 1992). Management practices suggested for secondary tropical forests include tree thinning, understory control, and opening crown cover to promote seed germination and natural regeneration (Brown and Lugo 1990). By these practices, the production of many useful forest goods can

be enhanced in secondary forests. Examples are logs, fuelwood, fruit, nuts, oils, medicinal plants, and local construction materials (Brown and Lugo 1990). To the extent that deforestation of mature forest is for the same goods, forest management practices that, as an alternative, provide them on deforested lands reduces the pressure to clear more mature forest, thereby conserving existing phytomass C.

The 1990 total plantation area in Brazil was 7 X 10^6 ha or only 0.8% of the nation's land area (FAO 1993). Key hardwood species are eucalyptus (i.e., *Eucalyptus deglupta* and *E. urophylla*) and melina (*Gmelina arborea*), and softwoods are predominantly pine such as *Pinus caribaea* var. *hondurensis* (McNabb et al. 1994). The proportion of hardwood plantations to softwood plantations is about two to one (Cottle et al. 1990). Fast growing plantations of these species are grown in 10- to 20-year rotations. High wood yields can be sustained and increased through economically attractive silviculture practices such as intensive site preparation, genetic improvement, fertilization, and particularly weed control throughout plantation rotation periods (McNabb et al. 1994). Plantation establishment continues in Brazil at roughly 450 X 10^3 ha/yr (WRI 1992). This annual planting rate should be sustained or perhaps expanded because in the future it is anticipated that more plantation wood will be needed in Brazil to meet increased demands in the paper and cellulose industries (Serrão and Homma 1993).

Thus with high growth rates and large areas of suitable land, the potential exists to sequester and conserve more C on forestlands in Brazil's Amazon region. Many approaches are possible such as (1) protect young secondary forests so that they continue to store and accumulate C, (2) convert more degraded pastureland to either secondary forests or to plantations, and (3) manage more efficiently mature forests such as is done by the extractive reserve projects (Serrão and Homma 1993).

The nation of Brazil must decide whether C mitigation through expansion of forest management is important to their interests. Vegetatively, the nation as a whole seems close to having a zero net C flux (Table VI.7), and it has only modest emissions through timber harvest and fossil fuels burning (Table VI.9). Growing more phytomass through expanding forest management, however, would (1) increase the nation's managed forest resources and reduce deforestation of mature forests, (2) provide a significant step toward sustainable development called for in 1992 at UNCED for all forested nations (Keating 1993), and (3) place Brazil in a position to participate in joint implementation forest projects with developed nations. These outcomes could offer Brazil added economic benefits and simultaneously sequester C to help reduce global atmospheric CO_2.

VII. Discussion: Comparison of the C Budgets for Four Nations

Natural terrestrial ecosystems and land-use types of the FSU, U.S. (48 conterminous states), Mexico, and Brazil total 3.92 X 10^9 ha (Table VII.1). The total land area of the world, excluding Antarctica, is 13.13 X 10^9 ha (WRI 1992). Thus, out of approximately 200 nations or territories in the world, the four case-study nations contain about 30% of the total land area. They also play a dominant role in the amount of land in three major vegetation and land-use types.

Closed forests: The four nations of this study contain approximately 1.26 X 10^9 ha or 35% of the world total which is 3.59 X 10^9 ha of closed forests (WRI 1992) (Table VII.1). Forest C densities (TEC) range from 184 to 271 MgC/ha (Table VII.2).

Woodlands: The four nations have 0.45 X 10^9 ha or 26% of the world total which is 1.70 X 10^9 ha of woodlands (WRI 1992) (Table VII.1). Woodland C densities (TEC) range from 88 to 173 MgC/ha (Table VII.2).

Croplands: The four case-study nations contain 0.57 X 10^9 ha of croplands or 38% of the world total of 1.48 X 10^9 ha (WRI 1992) (Table VII.1). Cropland C densities (TEC) range from 85 to 156 MgC/ha based mostly on soil C (Table VII.2).

Clearly, understanding the extent of the C dynamics of the four nations in this report contributes significantly to an understanding of the terrestrial C dynamics of the world.

Table VII.1. Land Area of Major Vegetation Types by Nation

Vegetation Type	FSU*		USA†		Mexico‡		Brazil§		Totals
	Land Area (X 10^6 ha)								
Forestland	Coniferous	461					Closed TMF	352	
	Decid. Hardwd	24					Other closed TMF	16	
	Decid. Softwd	138							
	Total	623	Forested	201	Forest	71	Total	368	1263
Woodland	Coniferous	150							
	Decid. Hardwd	11							
	Decid. Softwd	30			Woodland/				
	Total	191	Woodland	41	Scrub	66	Cerrado	156	454
Cropland							Agriculture in degraded lands:		
							TMF	10	
							Closed For.	100	
							Savannah	18	
	Arable	277	Cropland	155	Cropland	13	Total	128	573
Sub-totals		1091		397		150		652	2290
Other types		1041		368		46		179	1634
Totals		2132		765		196		831	3924

*Former Soviet Union from Table III.1. The sum of the area for forests and woodlands is 814 X 10^6 ha and is equal to the sum of the three forest types in Table III.1 which are subdivided here into their forest and woodland components based on Kolchugina and Vinson (1993d) and Ryabchikov (1988).

†Conterminous United States from Table IV.1.

‡Mexico from Table V.1.

§Brazil from Table VI.1. The total area for forest here is only for mature forests; i.e., does not include secondary forests which are estimated to have covered in 1990 17.4 X 10^6 ha in the degraded TMF type plus 17.6 X 10^6 ha in the degraded close forest type.

Table VII.2. Comparison of Carbon Densities Among Nations

Vegetation Type/ Component	C Density (MgC/ha)			
	FSU*	USA†	Mexico‡	Brazil§
Forest				
Phytomass	70	63	64	152
Litter & CWD	27	30	7	17
Soil	122	91	118	102
Total	219	184	189	271
Woodlands				
Phytomass	34	13	20	26
Litter & CWD	16	ND	2	2
Soil	123	79	77	60
Total	173	92	99	88
Croplands				
Phytomass	3	5	6	8
Litter & CWD	0	0	1	0
Soil	153	105	78	72
Total	156	110	85	80

*Values for forest and woodlands of the FSU are area-weighted means based on areas in Table VII.7 and C densities in Tables III.2, III.3, and III.5. Values for croplands are those for arable land in Tables III.1, III.2, III.3 and III.5.

†Values are area-weighted means for the conterminous United States as presented in Table IV.1.

‡Values for Mexico are means as presented in Table V.7.

§Values for Brazil on forest phytomass (i.e., of mature closed forests) and agriculture soil are area-weighted means based on Tables VI.2 and VI.4; the value for woodlands phytomass is a mid-point in the range 22-30 MgC/ha appearing in Table VI.4.

ND No datum

A. Carbon Pools

The terrestrial ecosystems of the world have been estimated to contain 560 PgC aboveground in phytomass, litter, and CWD; belowground estimates are 1100 to 1400 PgC in roots and soil C (Smith et al. 1993). The total range, therefore, is 1660 to 1960 PgC. The total aboveground and belowground C for the FSU, conterminous U.S., Mexico, and Brazil is estimated in this analysis to be 866 PgC (Table VII.3) or about 44-52% of the world total. Thus, on 30% of the land area of the world represented by the four nations, there is from 45% to 53% of the world's phytomass and soil C pool. Because of its vast size and large areas of C-rich forests, peatlands, and chernozem soils, the FSU alone contains about a third of the world's total terrestrial C pool with 601.1 PgC (Table VII.3).

For forests and woodlands, phytomass and soils (to a depth of 1 m) worldwide are estimated to contain 359 PgC and 787 PgC, respectively, for a total of 1146 PgC (Dixon et al. 1994). The estimated 354 PgC for the forests and woodlands of the four nations of this analysis is about 30% of the worldwide forest-woodland total (Table VII.3). The FSU and Brazil have the largest forest C pools with 138 and 109 PgC, respectively. The forest C pools of the U.S. and Mexico are significantly smaller at 37 and 14 PgC, respectively.

Trends in C densities seem to follow expected changes from boreal to tropical climates. For all nations, forests have more phytomass than woodlands or croplands by more than three fold (Table VII.2). The Brazilian moist tropical forest ecosystems have the highest phytomass density of 152 MgC/ha, which is more than double that for the more northerly forests. The latter forests are remarkably similar in phytomass density to each other

Table VII.3. Estimates of Carbon Pools for the Vegetation Types Common to All Four Nations, 1990

Vegetation Type/ Component	C Pool (PgC)				
	FSU*	USA†	Mexico‡	Brazil§	Total
Forest					
Phytomass	43.3	12.6	4.6	64.0	124.5
Litter & CWD	19.2	6.0	0.5	6.6	32.3
Soil	75.7	18.3	8.4	38.3	140.7
Total	138.2	36.9	13.5	108.9¶	297.5
Woodlands					
Phytomass	6.4	0.5	1.3	4.1	12.3
Litter & CWD	3.0	ND	0.1	0.3	3.4
Soil	23.5	3.2	5.1	9.4	41.2
Total	32.9	3.7	6.5	13.8	56.9
Croplands					
Phytomass	0.8	0.8	0.1	1.0	2.7
Litter & CWD	0	0	<0.1	0	<0.1
Soil	42.5	16.3	1.0	9.2	69.0
Total	43.3	17.1	1.2	10.2	71.8
Total - all vegetation types					
Phytomass	60.4	16.0	6.2	73.1	155.7
Litter & CWD	34.5	6.1	0.8	8.2	49.6
Soil	506.2	64.7	18.1	71.7	660.7
Total	601.1	86.8	25.1	153.0	866.0

*Values for forest, woodlands, and croplands of the FSU are the product of areas in Tables VII.1 and C densities in Table VII.2 (some differences due to rounding). Values for "all vegetation types" are from Tables III.5, III.6 and III.7.

†Values for forest, woodlands, and croplands for the conterminous United States are the product of areas in Table VII.1 and C densities in Table VII.2 (some differences due to rounding). Values for all vegetation types are from Table IV.2.

‡Values for Mexico are means as presented in Table V.6.

§Values for forest (mature closed), woodlands, and croplands for Brazil are the product of areas in Tables VII.1 and C densities in Table VII.2. The national totals are means of three estimates appearing in Table VI.5.

¶Secondary forests are estimated to have an additional 4.7 PgC based upon phytomass at 40 TgC/ha, litter/CWD at 2 TgC/ha, and soil at 92 TgC/ha (Table VI.4) and a land area of 35.0 X 10^6 ha (Table VI.1).

ND No datum

ranging (in MgC/ha) from Mexico at 64 to U.S. at 63 to the FSU at 70. For litter and CWD, the forest ecosystems of the U.S. and FSU are highest with estimates similar to each other at 30 and 25 MgC/ha, respectively. For soil C, the FSU is highest at 123 MgC/ha; however, estimates for the other nations are not too different, ranging from 91 to 118 MgC/ha. The total C density, however, remains highest in the Brazilian moist tropical forest, i.e., 271 MgC/ha (Table VII.2).

For woodlands and croplands, the FSU ecosystems have the highest C densities at 173 and 156 MgC/ha, respectively (Table VII.2). For cropland phytomass alone, the FSU is lowest at 3 MgC/ha. However, for soil C, these vegetation types in the FSU have C-rich chernozem soils associated with the temperate forest steppe region. These soils are very high in organic matter per ha (123 MgC and 153 MgC) when compared to that of the other three nations whose soil C ranges from 72 to 105 MgC/ha.

The C densities and pools appear to reflect the influence of climate on terrestrial ecosystems (Table VII.2). That is, the colder climates of the boreal and temperate latitudes have ecosystems with more C stored belowground than above, while the tropical ecosystems of Brazil under warm climates have the opposite trend (Barbour et al. 1987). Mexico does not fit the tropical pattern perhaps because of the strong human influence on landscapes within this country. These relationships among the C densities and pools of the world's ecosystems have historically influenced their management by practices designed to provide goods and services for human needs. As the world moves toward managing more ecosystems for sustainable development, these relationships will take on even greater significance.

B. Carbon Flux

In this section, an effort is made to bring the flux estimates from the case studies into a common framework. As has been noted, there is considerable variation in the quantity of information available for the different countries as well as relative importance of different carbon flux processes. Nevertheless, it will be important in advancing the implementation of the Framework Convention for Climate Change for cross-country comparisons to be made. The focus here is on net flux. Where ranges were reported in the case studies, a mid range value was used here. In some cases, data from the case studies had to be disaggregated; however, the net carbon flux values used here are in agreement with the values in Tables III.11, IV.4, V.8, VI.7, and VI.8.

The components of the land base flux (Table VII.4) have been separated from the set of all flux terms (Table VII.5). The land base flux is divided into a net biological term and a land-use term. The net biological flux refers to the expected change in C storage on the land base if no further anthropogenic impacts were imposed. The three components of the net biological flux are the net changes in the pools of phytomass, CWD (woody debris and litter), and soil organic matter.

With the exception of soil and woody debris losses associated with previous disturbances (inherited emissions), nonforest lands are considered to be in C equilibrium with regard to the net biological flux. The mature forest of Brazil and Mexico are also considered to be in C equilibrium. Caveats regarding this assumption have been discussed in the sections covering Brazil and Mexico. The effect of these assumptions is that a considerable proportion of the land-base in each country is considered to

Table VII.4. Land Base Carbon Flux for the Four Case Studies*

Land Base	C Flux (Tg/yr)			
	FSU	USA	Mexico[II]	Brazil[***]
Net Biological[†]				
Phytomass[‡]	453[♦]	366[#]	8.0	54[†††]
CWD[§] & Litter	103[I]	-34[§§]	-44.8[▲▲]	-75[##]
Soil	75[▲]	0	0.2	5[§§§]
Total	631	332	-36.6	-16
Land Use				
Harvest Removals[¶]	-101[☆]	-125[§§]	-2.6	-11
Harvest Emissions[♦]	-47[■]	-112[¶¶]	-1.6[☆☆]	-7
Conversion Emissions[♠]	0	-4[••]	-30.8[■■]	-132[¶¶¶]
Agricultural Emissions	-194[☆☆]	-2[♠♠]	0	-85[♦♦♦]
Total	-342	-243	-35.0	-235
Net	289[††]	89[••]	-72	-251[♠♠♠]

* Unless otherwise noted, the estimates are taken directly from the case study chapters. The approximate time period associated with the estimates varies somewhat by country. For the FSU the period is the late 1980s; for the USA it is the early 1990s; for Mexico it is the 1980s; and for Brazil it is 1990. This net land base flux also appears on Table VII.5.

† Net biological is the change in the pool, assuming no harvest or land use change.

‡ Tree growth less mortality.

§ Coarse woody debris. Includes decomposition on formerly disturbed lands.

¶ Harvest removals refer only to growing stock removed from the forest.

♦ Harvest emissions refer only to burning of tree C at the time of harvest.

♠ Conversion emissions refer to burning of tree, CWD, or soil C at the time of conversion.

♦ 520 (phytomass, Table III.11) - 67 (fires, Table III.11 and discussion in Section III.D.1.c, p. 44-46) = 453.

I 118 (CWD, Table III.11) - 15 (fires, Table III.11 and discussion in Section III.D.1.c) = 103, litter flux is not included.

▲ 53 (peat, Table III.11) + 5 (non-forest, soil, Table III.11) + 40 (forests, soil Table III.11) - 23 (fires, Table III.11 and discussion in Section III.D.1.c) = 75.

☆ 389 Mm^3 (Section III.D.1.c) of merchantable wood is harvested. This converts to 101 Tg using 260 TgC/m^3 (Section III.D.1.c).

■ 389 Mm^3 of merchantable wood converts to 148 Tg of tree carbon (Section III.D.1.c). 148 (tree C) - 101 (merchantable C) = 47 (slash C).

•• 100 (peat combustion, Table III.11) + 94 (agricultural land emission, Table III.11) = 194.

†† 292 (Table III.11) - [-30 CCH_4 emissions, Table III.11] - 33 (increase in products pool accounted for in Table III.11) = 289.

\# Tree + understory, Table IV.4.

§§ Table IV.4.

¶¶ -28 (litter, Table IV.4) + [-7 (understory, Table IV.4)] + [-77 (tree C, Table IV.4)] = (-112).

(continued)

Table VII.4 Continued

♦♦ Section IV.C.1.d.
♦♦ Table IV.5.
♦♦ Table IV.5, 95 (forest land base) - 4 (conversion emissions) - 2 (agricultural land base) = 89.
II Values from Table V.8.
▲▲ -45 (inherited emissions) + 0.2 (CWD + litter accumulation) = (-44.8).

☆☆ -2.6 (merchantable) x 1.6 (assumed ratio of tree C to merchantable C) = -4.2 (tree C harvested. Then (-4.2) - [-2.6, merchantable] = -1.6 (slash).
■■ Prompt emissions.
••• Based on Tables VI.7 (Olson biomass densities) and VI.9.
††† 44 (secondary forests) + 10 (pastureland) = 54.
18 (secondary forests) + (-93, pastureland) = -75.
§§§ 15 (secondary forests) + (-10, tropical moist forest) = 5.
¶¶¶ -97 (tropical moist forests + [(-35), cerrado] = -132.
♦♦♦ -75 (degraded closed forest) + [(-10), degraded savannah] = -85.
♦♦♦ -233 (Table VI.7) - [(-18), harvest removals and harvest emissions] = (-251).

Table VII.5. Net Carbon Flux for the Four Case Studies

Component	C Flux (Tg/yr)				
	FSU†	USA‡	Mexico§	Brazil¶	Total
Land base**	289	89	-72	-251	55
Forest products	33	36	1#	3	73
Energy*	-1,020	-1,296	-74	-50	-2,440
Cement*	-19	-10	-3	-3	-35
Net	-717	-1,181	-148	-301	-2,347

*Subak et al. 1993

†Values from Table III.11.

‡Values from Table IV.5.

§Values from Table V.8. Net flux of -148 here compares to -148.9 reported by Makundi et al. (1992) in Table V.8.

¶Values from Table VI.8.

#One half of the input to the forest products pool is assumed to be accumulating.

**Values from Table VII.4 in this row only.

be in C equilibrium (43% for FSU, 54% for the U.S., 86% for Mexico, and 86% for Brazil).

Considering only the net biological flux, the change in the phytomass pool—a balance of woody phytomass growth and mortality—is positive and relatively high in the FSU, the U.S., and Brazil because large areas of young forests promote C accumulation. The origin of these fluxes differs greatly: in the U.S., extensive logging; in FSU, extensive wildfire and anthropogenic disturbances; and in Brazil, extensive deforestation followed by reversion after abandonment. The annual change in CWD storage—a balance of natural tree mortality and decomposition—is negative in three of the nations. In the U.S. decomposition of woody residues in young secondary forests determines the sign of the flux. Woody debris is also a relatively large source of C in Brazil and Mexico because of decomposition of woody residue on pasturelands created within the last 10 years. The large C sink in the CWD pool of the FSU would be approximately 25 TgC/yr lower if the decomposition of logging residue was modeled as it was in the U.S. rather than as a component of the harvest emissions. The remaining CWD sink may be in part a function of a generally cooler climate which tends to slow the rate of decomposition.

The soil organic matter pool is a source in areas of active deforestation because of the imbalance of inputs from litter fall and fine root turnover and outputs from decomposition (i.e. inherited emissions). In Brazil, these soil emissions are counteracted by a large accumulation assumed to be occurring in the young secondary forests. The FSU budget also indicates a gain in soil C associated with secondary forests as well as a large sink from peat formation.

Besides the net biological flux, the other main land base flux is that associated with anthropogenic land uses. The components are (1) removal of wood during commercial forestry, (2) direct

emissions from phytomass burning (i.e. deforestation in the tropics and slash burns after timber harvests in the temperate and boreal countries), and (3) soil C emissions from tillage of agricultural soils (Table VII.4). Utilization of peatlands for fuel was included in the agricultural emissions.

Planned harvest removals were highest in the U.S. and Russia. In both cases over 100 TgC/yr of wood was removed from the forest land base. Smaller harvest removals in Brazil and Mexico reflect less industrial development, lack of infrastructure, few species identified to be commercially valuable, and less use of timber in construction. The direct emissions associated with commercial harvest are likewise largest in the U.S. and Russia because of the level of logging. Fuelwood removals are greater than commercial logging removals in the tropics but we have not made an attempt to isolate this flux; it tends to be a dispersed activity and is subsumed to some degree by other components of the C budgets.

The conversion emissions are greatest in Brazil (-132 Tg/yr) because of its high deforestation rate. Mexico also has a large source associated with deforestation (-31 Tg/yr). The land bases in the U.S. and FSU are relatively stable; thus, the land conversion emissions are quite low.

Agricultural lands in Russia are a 94 Tg/yr source and emissions from peatland utilization adds another 100 Tg/yr source. Agricultural lands in Brazil are extensive and represent a 85 Tg/yr source. Losses of soil C from tillage of agricultural lands in Mexico were not estimated separately here, but some losses may be captured in the estimate of inherited emissions. Much of the agricultural land in the U.S. has been under cultivation for many decades and, except for erosion, is probably approaching a steady state or even increasing due to improved soil conservation practices.

The sum of the four components of the land-use flux is largest in FSU (-342 Tg/yr), followed by the U.S. (-243), then Brazil (-235 Tg/yr), and Mexico (-35 Tg/yr). The net effect of the biological and anthropogenic factors on the land base is a C sink in the FSU and the U.S. and a C source in the tropical countries (Table VII.4).

In the complete country-level budgets, four additional flux components are included (Table VII.5). The accumulation of C in forest products still in use is greatest in the U.S. and FSU, which follows from the more extensive commercial logging in those countries. Accumulation in landfills is greatest in the U.S., but this flux is a relatively small term in these budgets. Emissions from energy use and production dominate the calculation of the U.S. and FSU budgets.

In all cases, C sources exceed C sinks, i.e. all countries are net emitters of C. The U.S. is the largest emitter because of its high per capita industrial emissions and large population. FSU has a similar distribution of sources and sinks, and like the U.S., is a large net emitter. Brazil is notable in that the net land-use source is larger than the industrial source. In Mexico, industrial emissions are of about the same magnitude as the net land base source. The summed net emissions from these four countries (230 Tg/yr) represents about 30% of the estimated global anthropogenic CO_2-C emission.

C. Policy Perspective and Prospects for Stabilization of Emissions

All four countries considered in this report make a significant contribution to global greenhouse gas emissions (Table VII.6) and have signed the Framework Convention on Climate Change (FCCC). Thus, they are committed to the policy stated in the FCCC, namely

Table VII.6 Greenhouse Warming Potentials

Country	TgC as CO_2 Equivalents (100-yr time horizon)*				
	CO_2	CH_4	N_2O	CFCs	Total
FSU	827	100	19	132	1,078
USA	1,241	98	56	357	1,752
Mexico	133	11	3	10	157
Brazil	269	38	10	13	330
Total	2,470	247	88	512	3,317
World	6,410	791	278	1,303	8,782

*Subak et al. 1993.

to stabilize atmospheric concentrations of greenhouse gases at levels that pose no threat to the planet. The quantitative meaning of this commitment and the policies that may be required for its implementation remains a subject for negotiation through the International Negotiating Committee.

Given the uncertainty regarding the meaning and implementation of the FCCC policy, no country has committed to a specific, long-term target for emissions. The U.S. has committed to an intermediate goal of reducing net emissions to the 1990 level by the year 2000. This goal, in conjunction with estimates of "business as usual" increases in emissions of greenhouse gases, commits the U.S. to off-setting 106 TgC/yr through a combination of decreased emissions and increased sinks (Clinton and Gore 1993). The lack of quantitative emission goals, and the lack of estimates of "business as usual" increases in emissions of greenhouse gases (a topic not considered in this report), restricts discussion of the potential for stabilizing emissions in the other countries to very general terms.

The four countries studied in this report differ greatly in the relative extent of CO_2 flux associated with the land base. In Mexico and Brazil the land base is a carbon source and that source appears to more than double emissions from other sources (see Table VII.4, VII.5). In these countries, land-use policies could potentially contribute substantially to implementing the FCCC policy.

In contrast, the land base plays a relatively small role in the net emissions from the U.S. Sequestration of carbon in terrestrial ecosystems and in forest products offsets less than 10% of the greenhouse gases emitted from other sources. Thus, the opportunities for conserving and sequestering C in the U.S. through changes in land use are relatively small. Nevertheless, land use may have a substantial role (i.e. 10-20%) in meeting the

intermediate national goal of implementing 106 TgC/yr of reduced-C-emission/increase-C-sequestration by the year 2000 (Clinton and Gore 1993) and in sustaining this achievement beyond 2000. In the absence of strong policy shifts over the next few decades, it appears that land use will play a continually decreasing role in offsetting industrial C emissions in the U.S.

In FSU, forest growth is estimated to offset up to 30% of emissions from other sources. Given the large forest land base, the opportunities to increase carbon sequestration rates appear to be significant. A possible counteracting factor will be potentially large increases in the harvest levels which may produce a carbon source in the near term.

VIII. Uncertainties and Research Needs

A. Global

In assessing C flux due to land-cover change, data are required for (1) classifying land cover and its relative change over time and (2) phytomass, or TEC, mass per unit area of the various land-cover classes—C density. Until recently, the most uncertain factor has been the accurate characterization of areal extent of land-cover classes through time and its resultant rate of land-cover conversion. Due to recent advances in satellite remote sensing and GIS technology, increasingly more accurate estimates of terrestrial land-cover change are becoming widely available. The C density and its change over time is now the limiting factor in accurate estimates of C flux due to changes in terrestrial biota. Because pasturelands and croplands typically possess C densities that are from one to two orders of magnitude less than the forest ecosystems they replace, attention is justifiably focused on the forest systems.

As interest in global C dynamics has grown in recent years, estimates of C pools and flux are required at larger spatial scales such as regions, nations, subcontinents, and even continents. Investigative research to provide the estimates have commonly relied on aggregating small-scale values for key components through multiplication and summation operations. The case studies in this analysis serve as examples. In simple terms, the total terrestrial C pool of each country was estimated by multiplying the mass of C/ha in phytomass and soil (usually from limited field data) for each vegetation type times number of hectares in that type (from vegetation maps), and then summing all products for a national estimate.

A concern is the degree of uncertainty in the estimates of C pools and flux at these large spatial scales. Robinson (1989) states "...error enters estimation through uncertainties and biases in the data, and compounds as data are combined to draw (often) lengthy chains of inferences." The subject is also referred to as error propagation.

Theoretically, if the variance around the value of each component in the chain calculation were known, statistical methods exist to determine the level of uncertainty for the estimate. The smaller the variances the less the overall uncertainty. Small variances, however, depend upon large representative samples, preferably taken randomly and with uniform methodology, in each homogeneous unit of every component in the chain. At the large spatial scales in national or global analyses, obtaining data in such a manner is currently not possible.

In terrestrial ecology, the issue is further complicated by a shortage of information on the belowground C density. These components have typically been estimated by applying factors developed from an even more limited amount of soil sampling around the world to the aboveground phytomass.

In time preliminary calculations of uncertainty in large-scale estimates of C pools and flux can be undertaken. Ongoing research is providing better data. For instance, more studies are focusing on the C density of phytomass and soil in more areas of the world. Better vegetation maps are being produced as a result of improved use of remote sensing from satellites together with increased ground-truth validation. Standard methodology is developing. One early improvement would be at least to have ranges around the values for chain components. Ranges along with clues about frequency distributions would enable first approximations in computations of uncertainty.

At present, most of the values in this document that are used for estimating national C pools and flux are based upon very limited data along with a few assumptions as discussed in each section. In general, the uncertainty issue underscores the research needs outlined above to make significant advances in the science of global environmental change in the next few decades. The modeling approaches, assumptions and data bases used for these analyses are supported by scientific literature as referenced. Projections of C dynamics compared favorably with those of other researchers.

Carbon density is most adequately understood in standing live aboveground phytomass because of its association with commercially important wood volumes. However, many forest ecosystems hold significant amounts of C in CWD aboveground and belowground in soils and roots. Globally, these C budget compartments offer areas for future research.

Processes important to understanding C dynamics and reducing C budget uncertainties include (1) phytomass accretion in regrowth forests following abandonment of pastureland or other agricultural uses, (2) carbon dynamics in small scale (1-2 ha) land uses causing forest degradation and subsequent recovery (e.g., milpa agriculture in Latin America), and (3) growth in mature forests which have been assumed to be in C equilibrium with the atmosphere.

Reducing uncertainties associated with the various forest ecosystem compartments and with the internal forest processes will only be achieved through intensive and extensive field research to validate and calibrate the models currently used to assess national and global C flux.

B. Boreal Zone

Accumulation of C in CWD, soil organic matter and peat is quite important in boreal countries because cool wet climates tend to slow decomposition rates. The frequency, areal extent, and intensity of forest fires is also critical because of the propensity for catastrophic wildfire. Because these forests may not have been of commercial interest, due to slow growth rates or inaccessibility, comprehensive information relevant to forest C budgets may not have been generated or be available. Data needs include information on forest inventories, CWD pools, allometric relationships, and rates of logging. Postharvest dynamics of soil C may be of particularly interest in the boreal zone because of the increased potential for soil waterlogging, another factor that may slow decomposition.

C. Temperate Zone

Large uncertainties are inevitably associated with working at the spatial and temporal scale of C budget studies at the national scale, and a number of specific issues relating to forest C dynamics need increased attention. In the temperate zone, the importance of an age-class based inventory has been discussed. Because of the economic importance of the forest sector, many countries appear to have reasonably complete inventories. However, approaches to inventory development and sampling intensity vary widely. Intercomparisons among approaches would be useful. For the U.S. in particular, an improved forest inventory on public lands is needed since historically the USDA Forest Service's Forest Inventory and Analysis units have surveyed only private timberland in the western U.S. where mostly the federal timberland is located (USDA 1992b). More generally, the inventory on forest lands reserved for habitat conservation

and recreation may not be tracked well because of the relatively low economic importance of these lands.

A better understanding of soil C and woody debris dynamics following harvest is also needed. Assumptions of significant losses in soil C after harvest, and gains later in stand development, which have been employed in earlier C budget models (Houghton et al. 1983; Heath and Birdsey 1993) may not be warranted in temperate zone forests. The dynamics of woody debris are also highly uncertain and will benefit from additional observations during forest surveys as well as more complex modeling approaches that account for stand history.

D. Tropical Zone

To date, C budgets for tropical nations or regions are based upon limited amounts of published data. Research is required to substantially increase the availability of data vital to more definitive estimates of C dynamics in tropical terrestrial ecosystems.

The C budgets of Mexico and Brazil presented here point to several key research needs. First, C budgets would be improved with more precise data on the areal extent of vegetation types and various land uses. The size of such areas is not clearly known in many tropical regions. In Mexico for instance, it is unclear how much agricultural land is used for pastureland versus the amount used for croplands.

Second, C density is another important general area of needed research. Within the cover and land-use types of the tropics, there is a general lack of data on C density as well as on the temporal changes caused by growth and disturbance, both natural and human-caused. Two vegetation cover types are of particular

interest, particularly in Brazil and Mexico: the mature and the secondary forests, which are both quite important to the overall accounting of C because of both their C density and their size.

For example, as noted in the Brazil section, despite high deforestation rates, there remains over 350 X 10^6 ha of mature forests. It has been suggested that many mature tropical forests are not in equilibrium, but actually experience net C accretion in response to natural and human-caused disturbances (Lugo and Brown 1992). Because of the large land areas involved, there is an important need to clearly determine the rate of change in C density of mature forests even if the annual rate of C sequestration per ha is small.

Both Brazil and Mexico have large areas of secondary forests resulting from past deforestation and other human disturbance (~70 and ~20 X 10^6 ha, respectively). Yet little is known about the exact extent of secondary forests in these and other tropical nations. Further, the C density or annual C uptake of these forests is not well known. Quantifying these secondary forest processes in tropical nations such as Brazil and Mexico is a vital missing segment of the world's terrestrial C budget (Skole et al. 1994).

Several other topics on which the availability of additional data would improve tropical C budgets warrant research attention. These include rates of land conversion such as deforestation, soil C contents and their rates of change following ecosystem disturbance, long-term C storage in wood products and landfills, the role of C transport by rivers (particularly for the Amazon basin), and assumptions about C equilibriums for the vegetation and land-use types as discussed in the Brazil and Mexico sections.

E. Carbon Dynamics Through Modeled Projections

The global C dynamics will likely continue to be impacted for at least several decades by human activities that cause high rates of CO_2 emissions and changes in vegetation and soil C pools. The dynamics of C at various scales need to be adequately projected to better understand the long-term consequences of these continued anthropogenic influences. Various vegetation and land-use change models are useful tools for projecting the results of changing C pools and flux, especially in forests. Examples follow.

1. Individual Tree Growth Models

Individual tree growth models have been developed that are based on physiological processes (Dixon et al. 1990). TREGRO (Weinstein et al. 1991) is an example of this type of model. TREGRO simulates flux of C, water and nutrients through a tree-soil continuum. Photosynthesis is calculated on an hourly basis, determined by the availability of resources such as light, water, and nutrients. Carbon is partitioned to various components based on phenology and the relative requirements of fixed C by the individual components. Tree growth can be simulated over a time frame of years.

Tree growth models do not simulate forest stand dynamics because they only consider growth of individual trees. They also do not consider ecological processes such as nutrient cycling or disturbance. However, individual tree growth models can be used to parameterize other models that do evaluate the vegetation dynamics of forest stands.

2. Forest Gap Models

Forest gap models were developed to simulate plant succession in a forest canopy opening (ca. 0.1 ha) caused by mature tree death or fall (Shugart et al. 1992). Tree growth is simulated by reference to empirical relationships among the growing tree, growing-degree days, and solar radiation. Recent developments include the addition of soil nutrients (e.g., FORTNITE, Aber and Melillo 1982; FORTNUT, Weinstein et al. 1982; LINKAGES, Pastor and Post 1985, 1986), soil water (FORENA, Solomon and Shugart 1984, Solomon 1986), seed dispersal (ZELIG, Urban et al. 1991), and high latitude environment (LOKI, Bonan 1991b).

The advanced forest gap models offer many advantages in assessing C pools and flux (King 1993a). These models couple ecological processes such as disturbance, nutrient cycling, water balance, and tree competition. Thus, they can simulate the response of forest stands to a changing environment. Disadvantages are that they require species-specific parameterization which can be quite detailed, tree migration is not simulated, and modeling the direct effects of atmospheric CO_2 is still being refined.

3. Biogeographic Models

Biogeographic models have been developed to simulate changes in natural vegetation at regional to global scales (Smith et al. 1993). The Holdridge Life Zone Classification System is an example of the simplest models, and it has been used to simulate the effects of climate change on the global distribution of vegetation (Prentice 1990, Smith et al. 1992). More sophisticated models are now available such as BIOME (Prentice et al. 1992), CCVM (Lenihan 1992), and MAPPS (Neilson et al. 1992).

BIOME, CCVM, and MAPPS have certain advantages: they are based on plant physiological principles and their simulations of vegetation distribution, based on changing climates, are likely to be more robust than those based only on correlation (King 1993a). The mechanistic treatment of water balance allows an evaluation of CO_2 effects on plant distribution. Also, since these are broad-scale models, they can be used as tools for assessing forest management effects on C dynamics. The main disadvantages of these models are that they were developed for equilibrium approaches and fail to simulate transient vegetation response to climate change.

4. Ecosystem Process Models

Several vegetation productivity models are being used to examine the potential effects of global change on NPP and biogeochemical cycles. These models attempt to simulate the processes of plant energy dynamics and C balance at the canopy level. The consideration of ecosystem C dynamics allows the simulation of changes in net C flux for a given location under changing climatic conditions (Smith et al. 1993). Such information could be valuable for large-scale C budget analysis if coupled with spreadsheet models such as COPATH (Makundi et al. 1991). Ecosystem models such as CENTURY (Parton et al. 1988), FOREST-BGC (Running and Coughlan 1988), and GEM (Rastetter et al. 1991) are useful for C dynamics evaluations because they are based on plant physiological and ecosystem processes.

The main advantage of ecosystem models is that they couple vegetation productivity with water balance and nutrient availability. In GEM, C allocation and dynamics in response to changing climate can be simulated from year to year (Rastetter et al. 1992). Ecosystem models require an enormous number of parameters, many which are lacking data or poorly understood.

5. Modeling Terrestrial Carbon Dynamics

Recent modeling efforts have investigated the potential transient response of vegetation to climate change and the impact on terrestrial C pools and flux. Regional and global C models are used to simulate C dynamics based on various climate scenarios. Examples include PULSE (Neilson 1990; King and Neilson 1992), IMAGE 2 (Vloedbeld and Leemans 1993), and the Holdridge bioclimatic model (Smith and Shugart 1993).

The PULSE model tracks forest tree dieback and regrowth to estimate the possible magnitude of C flux (Neilson 1990; King and Neilson 1992). Carbon loss to the atmosphere is simulated through an exponential decay process, while C sequestration by forest trees is simulated by a logistic function constrained by maximum C density. PULSE was developed for non-tropical forests.

The IMAGE 2 model projects changes in land cover as well as plant physiological processes and industrial production to simulate C flux between the terrestrial biosphere and atmosphere (Vloedbeld and Leemans 1993). IMAGE 2 explores C flux based on atmospheric CO_2 concentrations, water-use efficiency, plant photosynthesis and respiration, and changes in vegetation cover and agricultural-use patterns with the subsequent effects on land-use change.

In another global modeling effort, Smith and Shugart (1993) used the Holdridge Life Zone Classification to simulate the potential impacts of global climate change on patterns of potential terrestrial C storage and flux with the atmosphere. The Holdridge bioclimatic model relates current vegetation distribution to global climate patterns and potential impacts of climate change. Climate change scenarios were based on general circulation model predictions for an atmosphere with doubled CO_2

concentration. Current estimates of C pools in vegetation and soil are then used to calculate changes in potential terrestrial C reserves given the climate change scenario.

6. Land-Use Change Models

The models presented above are used to assess C dynamics at various temporal and spatial scales. The function of these models is based mainly on climate, vegetation distribution, and/or plant physiological processes. Only the IMAGE 2 model includes land-use change as a parameter in calculating changes in C pools and flux (Vloedbeld and Leemans 1993). IMAGE 2 is unique in its ability to simulate changes in land cover and land use by considering socioeconomic factors such as regional population and gross national product (Vloedbeld and Leemans 1993). These drivers set the demand for forestland conversion to agricultural land. The transitions from original land cover to agricultural land is used to determine the immediate C flux into the atmosphere with the emission rate dependent on environmental factors and the C content of the various pools.

7. Spreadsheet Modeling of Carbon Dynamics

The impact of terrestrial ecosystem processes on climatic change and C cycling is significant. However, several efforts to quantify and balance the global C budget have not been successful. These attempts have been constrained due to unreliable data on the role of vegetation and soil as a net C source or sink and the rate of land-use change. One way to balance the global C budget is the effort to understand the C dynamics at the regional and country scale. One approach is the COPATH spreadsheet model (Makundi et al. 1991). The spreadsheet format allows entry of inventory data such as forest type, land area, and various C pools.

COPATH is a unified approach to estimate C pools, flux and the rate of deforestation in the major forested countries of the world. The aggregation of the country-level C assessments can be used to assess climate and land-use implications at the global scale. A disadvantage of COPATH is that process-based simulations such as vegetation response to increasing atmospheric CO_2 or temperature changes cannot be assessed. However, COPATH could be linked with processed-based ecosystem or biogeographical models to overcome this limitation.

8. Modeling of Carbon Dynamics: In Conclusion

The models suggested above are only examples, and they are not all inclusive regarding available models. Detailed discussions of modeling C dynamics as it relates to global change and forests are presented by King (1993a) and Smith et al. (1993). Over time, projections of forest C pools and flux through modeling and with improved data will further advance the understanding of global C dynamics as well as how it is influenced by human activities.

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