

US EPA ARCHIVE DOCUMENT

The Terrestrial Carbon Cycle: Managing Forest Ecosystems

Statement of the Problem

The accumulation of CO₂ in the atmosphere due to fossil fuel use, deforestation and other anthropogenic sources is changing the global climate (Harries *et al.* 2001; IPCC 2002). Current understanding of the global carbon cycle suggests that managing forests and agricultural lands to increase the sequestration of greenhouse gases (GHG) provide credible policy options (Dixon and Turner 1991, Winjum *et al.* 1993a, Brown 1996a, Brown *et al.* 1996). EPA/WED research efforts during the 1990's estimated the amount of that carbon which could be sequestered by purposeful management actions, and the incidental amount of carbon that inadvertent land use is likely to release to the atmosphere in the future. The three specific objectives of this research were to: 1) develop or refine global, country-level and regional estimates of carbon pools and fluxes in forests, 2) evaluate the potential to conserve and manage forests to expand the accumulation of carbon, and, 3) project future forest carbon pools and fluxes during expected changes in climate and land-use. The annual exchange of carbon between forests and the atmosphere, and the amounts of carbon stored in forests, varies widely with the nature of forest cover. With land use and management, and with climatic constraints, our research showed that management of forests can significantly increase the long-term sequestration of atmospheric CO₂. However, management efforts aimed at storing carbon in the tropics -- the largest pools on Earth -- are being countered by carbon emissions from forest destruction.

Approach

We developed several methods to quantify the major carbon pools and fluxes in forested ecosystems (Winjum *et al.* 1993b, Turner *et al.* 1995, 1997, Brown *et al.* 1999). Forest carbon budgets were constructed with recently completed national carbon budgets, and with global, national or regional databases of carbon densities in various above and below-ground forest pools (Dixon and Turner 1992; Kolchugina and Vinson 1993a; Cairns *et al.* 1997), in forest products (Winjum *et al.* 1998), and in differing land uses (Brown 1996b) and forest areas (Gaston *et al.* 1994,1997). NHEERL researchers applied available static geographic models (Turner and Leemans, 1992; King and Neilson 1992, Lugo *et al.* 1999) or developed new models (Prentice *et al.* 1992; Solomon *et al.* 1993; Neilson 1995; Kirilenko and Solomon 1998), each using the distributions of current climate variables as proxies for vegetation and carbon stocks. The data sets and information developed in these studies were then used as a base against which to contrast the amounts of carbon that is sequestered by various management techniques (e.g., Winjum *et al.* 1993b, Dixon 1995, 1997; Dixon *et al.* 1993, 1994b). The distribution of future climatic conditions projected by climate models could then be used to assess distributions and amounts of future carbon stocks. The future global carbon stock estimates from the static geographic models are discussed under "*F-Vegetation Redistribution*" and will not be reiterated here.

Main Conclusions

Forests play a prominent role in the global carbon cycle and the accumulation of GHG in the atmosphere, but the roles vary regionally (Dixon *et al.* 1994). In the conterminous United States, for example, total forest carbon was calculated to be 36.7 Gt C (Gt = Gigatons, i.e., a billion tonnes), with annual uptake of about 331 Mt (million tons) C, and losses to harvests of 266 Mt C (Turner *et al.* 1995). However, a different method suggested that annual carbon uptake for eastern U.S. forests during the late 1980s and early 1990s was about 416 Mt C/yr (Brown and Schroeder 1999). In the eastern United States, forest carbon stocks were estimated at 20.5 Gt, 80% of that found in hardwoods (Brown *et al.* 1999). Schroeder *et al.* (1997) noted that these carbon stocks were distributed primarily in small stands or lots with small trees, and in larger stands with large trees. This suggests that most carbon in the eastern U.S. is stored in young forests growing on abandoned farms and in forest reserves with large mature trees. An error analysis of the southeastern carbon stocks (Phillips *et al.* 2000) showed that sampling error was only about 1% (95% confidence intervals) but that annual carbon increments carried errors of about +/- 40%.

These carbon stocks and fluxes from the temperate U.S. forests were compared to estimates we developed in boreal and tropical regions, and for the world as a whole. Globally, forest vegetation and soils contain about 1146 Gt of C, with approximately 37% of this carbon in low-latitude forests, 1/7 in mid-latitudes, and 49% at high latitudes. Over two-thirds of the carbon in forest ecosystems is contained in soils and associated peat deposits (Dixon *et al.* 1994a). The carbon stocks and fluxes of the former Soviet Union (FSU) were examined in several papers which focused on the large portion of the world's biomass held by the boreal forests and peatlands.

Based on calculations from mapped ecoregions of the FSU, and estimated carbon stocks and fluxes in those ecoregions, the FSU forests were estimated to contain 69 and 110 Gt C above ground, and 331 and 337 Gt C below ground (Kolchugina and Vinson, 1993b and 1993c, respectively). A third paper in the series (Vinson and Kolchugina 1993) indicated similar values of 118 Gt C above ground for all vegetation, and 423 Gt C below ground. Unique environments (permafrost, peatlands) of the FSU were analyzed separately, indicating that permafrost carried 17 Gt C above ground and 155 Gt C in soils and litter (Kolchugina and Vinson 1993d, 1993e), including peatland carbon. Carbon in peatlands evaluated alone (Botch *et al.* 1995) was estimated at 215 Gt C.

Estimates of carbon stocks and fluxes from several tropical regions provided additional depth to the analysis. Africa, for example, was determined to contain 50.6 Gt C in all vegetation cover, both above and below ground (Gaston *et al.* 1998). In the western Hemisphere, Brazil contains the world's largest expanse of tropical forests, with 136-162 Gt C in above and below-ground vegetation and litter (Schroeder and Winjum 1995a), and net emissions of carbon to the atmosphere of 174-233 Mt yearly (Schroeder and Winjum 1995b) projected for the 20-yr period of 1990 to 2010 (Schroeder and Winjum 1995c, Schroeder 1996). Delany *et al.* (1997, 1998) determined that Venezuelan forests held 300-

500 T/ha C, with 20-37% of that on and below ground and with turnover time of litter into CO₂ being very rapid (<2 yrs). Biomass burning in Costa Rica (Helmer and Brown 2000) contributed to considerable CO₂ emissions as well, primarily from lowland forest destruction.

In Mexico, like Costa Rica, most carbon stock changes near the end of the 20th century were attributable to destruction of tropical and subtropical forests (Cairns *et al.* 1995, 1996), from southern Mexico (Riley *et al.* 1997, Schuft *et al.* 1998, Cairns *et al.* 2000), to the Mexican central highlands (De Jong *et al.* 1999, 2000). The data from Brazil, Mexico, the U.S. and the former Soviet Union, were combined in several papers, both for comparing overall carbon budgets (Turner *et al.* 1997, 1998, without Mexico), and to compare land use effects (Cairns *et al.* 1997). The results amplified conclusions reached in earlier analyses, demonstrating the importance of reducing land use impacts on forest biomass in tropical areas, and of applying forest management techniques to enhance carbon sequestration in tropical, temperate and boreal regions.

Slowing deforestation, combined with an increase in forestation and other management measures to improve forest ecosystem productivity, could conserve or sequester significant quantities of C. Future forest carbon cycling trends attributable to losses and regrowth associated with global climate and land-use change are uncertain (Dixon *et al.* 1999). Model projections and field experiments suggest that forests could be carbon sinks or sources in the future (Dixon *et al.* 1994). To the end, forest carbon conservation and sequestration options have become major policy instruments of the UN Framework Convention on Climate Change Activities (UNFCCC) Implemented Jointly (AIJ) pilot over the past decade (Dixon 1999, Dixon 1995).

Estimates of carbon pools and flux in forest vegetation in world forests

Latitudinal Belt	C Pools (Pg)	
	Vegetation	Soils
<i>High</i>		
Russia	74	249
Canada	12	211
Alaska	2	11
Subtotal	88	471
<i>Mid</i>		
Cont'l US	15	26
European ^a	9	25
China	17	16
Australia	18	33
Subtotal	59	100
<i>Low</i>		
Asia	41 ^b -54	43
Africa	52 ^b	63 ^c
Americas	119 ^b	110 ^c
Subtotal	212	216
TOTAL	359	787
1Pg=10 ¹⁵ g or 1 gigatonne		

The table shows estimated carbon pools and area-weighted carbon densities in forest vegetation (above- and below-ground living and dead mass) and soils (O horizon, mineral soil to a depth of 1 m, and co-located peatlands) in forests of the world (from Dixon et al 1999).

a Includes Nordic nations. A factor of 1.75 was used to convert stem to total vegetation biomass. For soil C, an average of 9 kg m² for temperate forests and the forest area in Table 1 was used.

b Estimated as the product of carbon densities by ecofloristic zone and areas of forest in each zone, corrected for roots, non-tree components, and woody debris.

c Estimated as the product of forest area and an average of 12 kg m² of soil organic C.

Forests are important in the global carbon cycle because they store more than 55% of the global carbon stored in vegetation and more than 45% of that stored in soils, exchange carbon with the atmosphere through photosynthesis and respiration, are sources of atmospheric carbon when they are disturbed by human or natural causes and become atmospheric carbon sinks during regrowth after disturbance. Forests can influence climate change by affecting the level of CO₂ in the atmosphere; through the production of other greenhouse gases such as carbon monoxide, ozone, and nitrous oxide; and through changes in albedo of land as forests are converted to other land cover types.

Globally, forest vegetation and soils contain approximately 359 and 787 Pg of C, respectively (Pg= 1,000 million tonnes). Earlier projections ranged from 953 to 1400 Pg of global C. The allocation of carbon between vegetation and soils differs by latitude, with a large part of the vegetation (25%) and soil (59%) carbon pools located in the high-latitude forests. Mid-latitude forests account for a small portion of the global carbon pool (16 and 13% of the vegetation and soil, respectively). Low-latitude tropical forests are relatively heterogeneous and contain 59 and 27% of global forest vegetation and soil C, respectively (Dixon et al. 1994a).

Carbon Sequestration Potential

Global estimates of potential amount of C that could be sequestered and conserved by forest management practices between 1995 and 2050 (from Brown *et al.* 1996a)

Latitudinal Belt	Country/Region	Practice	C Sequestered/Conserved (Gt)	
High	Canada	Forestation	0.68	
	Nordic Europe		0.03	
	FSU		1.76	
	Subtotal		2.4	
Mid	Canada	Forestation	0.43	
	USA		3.07	
	Europe		0.96	
	China		1.70	
	Asia		2.19	
	South Africa		0.44	
	South America		1.02	
	Australia		0.31	
	New Zealand		1.7	
	Subtotal		11.8	
	USA		Agroforestry	0.29
	Australia		0.36	
	Subtotal		0.7	
Low	Tr. America	Forestation	8.02	
	Tr. Africa		0.90	
	Tr. Asia		7.50	
	Subtotal		16.4	
	Tr. America	Agroforestry	1.66	
	Tr. Africa		2.63	
	Tr. Asia		2.03	
	Subtotal		6.3	
	Tr. America	Regeneration ²	4.8-14.3	
	Tr. Africa		3.0-6.7	
	Tr. Asia		3.8-7.7	
	Subtotal	11.5-28.7		
	Tr. America	Slow Deforestation ¹	5.0-10.7	
Tr. Africa	2.5-4.4			
Tr. Asia	3.3-5.8			
Subtotal	10.8-20.8			
Total		60-87		

¹Includes an additional 25% of aboveground C to account for belowground C in roots, litter, and soil (based on data in Brown *et al.*, 1996); range in values is based on the use of low and high estimates of biomass C density resulting from the uncertainty in these estimates.

Humans change the size of carbon pools and alter the flow of carbon between them through forest management. Forests can become atmospheric carbon sinks during regrowth and can be managed to alter their role in the carbon cycle. Local forests management for carbon conservation and sequestration could mitigate emission of carbon CO₂ by an amount equivalent to 11 to 15 percent of fossil fuel emissions (Brown *et al.* 1996).

Estimates of unrealized global forest carbon conservation and sequestration range from 1 to 3 Pg C annually for as much as a century. Forest management practices to conserve and sequester carbon can be grouped into four major categories: 1) maintain existing carbon pools (e.g., slow deforestation) (Dixon *et al.* 1993), 2) expand existing carbon sinks and pools through forest management (Dixon 1997), 3) create new sinks and pools by expanding tree and forest cover (Winjum *et al.* 1992), and, 4) substitute renewable wood-based fuels and products for those derived from fossil fuels (Dixon *et al.* 1994b). Management of forests as carbon reservoirs often complements other environmental goals including protection of biologic, water, and soil resources.

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Annotated Bibliography of WED Research

Börner, T., M.G. Johnson, P.T. Rygielwicz, D.T. Tingey and G.D. Jarrell. 1996. A two-probe method for measuring water content of thin forest floor litter layers using time domain reflectometry. *Soil Technology* 9: 199-207.

Few methods exist that allow non-destructive in situ measurement of the water content of forest floor litter layers (Oa, Oe, and Oi horizons). Continuous non-destructive measurement is needed in studies of ecosystem processes because of the relationship between physical structure of the litter and the biological and chemical processes that take place therein. We developed a method using time domain reflectometry (TDR) to monitor water content in a coniferous forest floor litter layer. Litter and mineral soil horizons were reconstructed in test beds in which TDR probes were placed and measurements taken using a range of litter and mineral soil water contents. Two probes are necessary when litter thickness is less than the spatial sensitivity (6 to 8 cm) of the TDR probes; one probe placed in the mineral soil and another one at the interface of the litter and mineral soil. Using this arrangement of TDR probes and simple mathematical relationships, the volumetric water content of forest litter can be estimated continuously. When the results of the two-probe method are compared to volumetric water content of forest litter obtained by gravimetric means there is a strong positive linear relationship between the two measured values of litter water content $r^2 = 0.93$). The two-probe method, however, underestimates litter water at low water contents and overestimates it at high water contents. This error has at least three components: (1) TDR instrument error, (2) errors in estimating volumetric water content from gravimetric data, and (3) using a TDR calibration curve not specific for high organic matter litter layer material. Calibrating the instrument for this specific condition should improve the overall estimate of the litter layer water content.

Botch, M.S., K.I. Kobak, T.S. Vinson and T.P. Kolchugina. 1995. Carbon pools and accumulation in peatlands of the former Soviet Union. *Global Biogeochemical Cycles* 9:37-46.

To date, the areal extent, carbon pools, rate of carbon accumulation, and role of peatlands of the former Soviet Union (FSU) in the terrestrial carbon cycle has not been fully recognized. This is a consequence of the fact that many peatlands in the FSU, especially noncommercial peatlands, were never studied and properly mapped. An estimate of the areal extent, carbon pools, and rate of carbon accumulation in peatlands of the FSU obtained by interrelating a number of regional databases and maps, including formerly classified maps, is presented herein. Commercial peatlands were categorized by regional type which facilitated an evaluation of their age and quality. Noncommercial peatlands were evaluated from classified regional topographic maps. Air photographs were used to identify peatlands of northern landscapes. The total peatland area of the FSU was estimated at 165 Mha (10^6 hectares) which was two times greater than the most recent estimates based on thematic maps. The peat

carbon pool was estimated at 215 Pg C. Half of this amount was in raised bogs. The rate of peat accumulation varied from 12 g C m⁻² yr⁻¹ (polygonal mires) to 72-80 g C m⁻² yr⁻¹ (fens and marshes). The total rate of carbon accumulation in FSU peatlands was 52 Tg C yr⁻¹. Carbon emissions from peat utilization in the FSU were estimated at 122 Tg C yr⁻¹. Thus, at present, peat accumulation/utilization in the FSU is a net source of approximately 70 Tg C yr⁻¹ to the atmosphere.

Barker, Jerry R., Greg A. Baumgardner, Jeffrey J. Lee and J. Craig McFarlane. 1996. Land use, the climate change action plan, and U.S. Department of Defense forests. World Resource Review 8:23-35.

The Climate Change Action Plan (CCAP) commits the United States to reducing green house gas emissions to their 1990 levels by the year 2000. Management to improve carbon (C) sequestration by forests may be one way to offset increasing atmospheric greenhouse gas concentration. A forest-inventory model and a forest-carbon model were used to calculate C pools and fluxes for the forests of Camp Shelby—a military training base in Mississippi. Research objectives were to model C pools and fluxes from 1990 through 2040, and to account for on-site and off-site C benefits as they relate to achieving the CCAP in Mississippi. In comparison with conservation management, tree harvesting for merchantable logs, fuelwood, or land-use change decreased C pools and sequestration rates, while reforestation increased C pools and sequestration rates. The production of lumber or fuelwood from the harvested trees contributed to off-site C benefits. However, only fuelwood produced long-term, off-site C benefits adequate to offset on-site C losses from harvesting trees. The reforestation scenario could provide about 1.3% of the C offset needed to obtain the CCAP in Mississippi

Barker, J.R., G.A. Baumgardner, D.P. Turner, and J.J. Lee. 1996. Carbon dynamics of the conservation and wetland reserve programs. Journal of Soil and Water Conservation 51:340-346.

Data from the Conservation (CRP) and Wetland (WRP) Reserve Programs were analyzed to quantify the carbon (C) dynamics of associated cropland converted to grassland or forestland. Land-area enrollments were multiplied by grassland- and forestland-C densities to calculate C pools and fluxes 50 years into the future. The CRP began in 1986 and by 1996 consisted of 14.7 Mha (3.6 X 10⁷ a) of grassland and 1.5 Mha (3.7 X 10⁶ a) of forestland. CRP1 scenario simulated the likely outcome of the CRP as contracts expire in 1996 with the return of 8.7 Mha (2.1 X 10⁶ a) of grassland and 0.4 Mha (9.9 X 10⁵ a) of forestland to crop production. CRP2 scenario assumed that the CRP continued with no land being returned to agricultural use. CRP3 scenario was an expansion of CRP2 to include afforestation of 4 Mha (9.9 X 10⁶ a) of new cropland. The WRP began in 1996 with 2 Mha (4.9 X 10⁶ a) of river bottomland taken out of crop production and planted to hardwood trees. Conclusions of the research were

(1) that cropland converted to forestland gained C at a rate about 7 times greater than cropland converted to grassland; (2) maintaining the existing CRP grassland will provide a substantial C sequestration potential because of the large area involved; and (3) afforestation of additional cropland would increase the potential to sequester atmospheric C for any years.

Barker, Jerry R., Greg A. Baumgardner, David P. Turner and Jeffrey J. Lee. 1995. Potential carbon benefits of the conservation reserve program in the United States. *Journal of Biogeography* 22:743-751.

Three scenarios of the Conservation Reserve Program (CRP) were simulated to project carbon (C) pools and fluxes of associated grassland and forestland for the years 1986-2035; and to evaluate the potential to offset greenhouse gas emissions through C sequestration. The approach was to link land-area enrolments with grassland and forestland C densities to simulate C pools and fluxes over 50 years. The CRP began in 1986 and by 1996 consisted of 16.2×10^6 ha cropland converted to 14.7×10^6 ha grassland and of 1.5×10^6 ha forestland. The CRP1 simulated the likely outcome of the CRP as contracts expire in 1996 with the anticipated return of 8.7×10^6 ha grassland and of 0.4×10^6 ha forestland to crop production. The CRP2 assumed that the CRP continues with no land returning to crop production. The CRP3 was an expansion of the CRP2 to include afforestation of 4×10^6 ha new land. Average net annual C gains for the years 1996-2005 were <1, 12, and 16 TgC yr⁻¹ for CRP1, CRP2, and CRP3, respectively. Afforestation of marginal cropland as simulated under CRP3 could provide approximately 15% of the C offset needed to attain the Climate Change Action Plan of reducing greenhouse gas emissions to their 1990 level by the year 2000 with the United States.

Beedlow, Peter A, David T Tingey, Donald L Phillips, William E Hogsett, and David M Olszyk. 2004. Rising atmospheric CO₂ and carbon sequestration in forests. *Front Ecol Environ* 2(6): 315–322.

Rising CO₂ concentrations in the atmosphere could alter Earth's climate system, but it is thought that higher concentrations may improve plant growth through a process known as the "fertilization effect". Forests are an important part of the planet's carbon cycle, and sequester a substantial amount of the CO₂ released into the atmosphere by human activities. Many people believe that the amount of carbon that forests sequester will increase as CO₂ concentrations rise. An increasing body of research suggests, however, that the fertilization effect is limited by nutrients and air pollution, in addition to the well documented limitations posed by temperature and precipitation. This review suggests that existing forests are not likely to increase sequestration as atmospheric CO₂ increases. Therefore, it is imperative that we manage forests to maximize carbon retention in above- and belowground biomass and conserve soil carbon.

Bormann, B.T., P.S. Homann, L. Bednar, M.A. Cairns and J.R. Barker. Field Studies to Evaluate Stand-Scale Effects of Forest Management on Ecosystem Carbon Storage. IAG DW12936179, Programmatic Plan.

This research will provide new knowledge on the range of possibilities-available by managing forests differently-to store more carbon (C) to meet the climate-change action plan (Clinton and Gore 1993) target of returning emissions of greenhouse gases in the United States to 1990 emissions by the year 2000.

Our specific goals are to:

- Evaluate effects of forest management strategies on stand-scale C conservation and sequestration,
- Improve the quality and applicability of stand-scale C budgets and methods, and
- Blend research programs within the Corvallis EPA and PNW labs.

To achieve our goals, we will simultaneously evaluate and improve hypotheses, a database, and C-measurement methods.

We will measure forest C pools and, to a lesser extent, C fluxes in a variety of stands in the Pacific Northwest. Belowground C pools, which are not considered in many studies, will be determined. Our strategy is to draw on the strengths of retrospective, long-term, and small-scale field studies and experiments, evaluated in parallel. This field research will rely heavily on existing studies and experiments, and on collaboration between EPA and the Pacific Northwest Research Station (PNW) especially the PNW Long-Term Ecosystem Productivity Program (LTEP)-and other agencies and universities. Pretreatment C pools and their associated uncertainties will be determined for the five PNW-LTEP long-term sites across Oregon and Washington. This information will provide a baseline to determine the effects of the future experimental manipulations (vegetation composition, amounts of woody debris).

Brown, Sandra. 1996. Tropical forests and the global carbon cycle: estimating state and change in biomass density. *In* The Role of Forest ecosystems and Forest Management in the Global Carbon Cycle. M. Apps and D. Price, editors. NATO ASI Series, Springer-Verlag, 140:135-144.

Tropical forests have an important role in the global carbon (C) cycle because of their existing large areal extent, high rates of deforestation, large C pool in vegetation and soil, and high rates of C emissions resulting from conversion to other uses (equivalent to between 22 and 37% of current fossil fuel C emissions) (Table 11.1). Tropical forests currently account for about 43% of the global forest area (Dixon et al. 1994). most of which is in tropical America (52%), followed by tropical Africa (30%) and tropical Asia (18%). They occur mostly as lowland formations where 88% are at an

elevation of 1000 m or less. Within the lowlands, 47% are in the rain forest ecological zone, 38% in the moist deciduous zone, and 15% in the dry to very dry zone (Food and Agriculture Organization (FAO) 1993).

During 1981-90, the average rate of deforestation was about 15.4 Mha yr⁻¹ (Table 11.1). The area deforested in tropical America was almost twice as high as in the other two continental regions, but tropical Asia had the highest rate of deforestation relative to its remaining forest area. In addition to deforestation, logging affects another 5.6 Mha, with over 80% of this from mature forests, and the remainder from previously logged forests (Table 11.1). Therefore, deforestation and harvesting alone affect a total of 21 Mha yr⁻¹. In addition tropical forests are subject to various forms of degradation, including decrease in canopy density (e.g., transformed from closed to open forest formations), fragmentation (partial deforestation), and conversion to other wooded classes such as shrubs or short-fallow agriculture (Brown et al. 1993; FAO 1993). It is estimated that rates of conversion to degraded forests are several times higher than rates of deforestation (FAO 1993).

Brown, S. 1996. Present and potential roles of forests in the global climate change debate. *Unasylva* 185:3-9.

Forests have the potential to contribute to climate change through their influence on the global carbon cycle. They store large quantities of carbon in vegetation and soil, exchange carbon with the atmosphere through photosynthesis and respiration, release carbon into the atmosphere when they are disturbed, become atmospheric carbon sinks during regrowth after disturbance and can be managed locally, to alter their role in the carbon cycle. Recent studies suggest that local management of forests for carbon conservation and sequestration could mitigate emissions of carbon dioxide by an amount equivalent to 11 to 15 percent of fossil fuel emissions over the same period.

Brown, Sandra. 1997. Forest and climate change: Role of forest lands as carbon sinks. Invited paper for the XI World Forestry Congress, October 1997, 15 pages.

Forests potentially contribute to global climate change through their influence on the global carbon (C) cycle. They store large quantities of C in vegetation and soil, exchange C with the atmosphere through photosynthesis and respiration, are sources of atmospheric C when they are disturbed, become atmospheric C sinks during abandonment and regrowth after disturbance, and can be managed to alter their role in the C cycle. The world's forest contain about 830 Pg C (10^{15} g) in their vegetation and soil, with about 1.5 times as much in soil as in vegetation. During the 1980s, analysis of C budgets show that forest of the temperate and boreal countries were a net sink of atmospheric C of about 0.7 Pg yr⁻¹, but the tropics were a net source of about 1.6 Pg yr⁻¹. However, accounting for the imbalance in the global C cycle suggests that forest are not significantly contributing to the net increase in atmospheric CO₂ and thus not

contributing to global climate change. However, this may not continue into the future as temperate and boreal forests reach maturity and become a smaller C sink, and if rates of tropical deforestation and degradation continue to accelerate. Recent studies suggest that there is the potential to manage forests to conserve and sequester C to mitigate emissions of carbon dioxide by an amount equivalent to 11-15% of the fossil fuel emissions over the same time period. Aggressive adoption of these forest management options are necessary to prevent forests becoming a significant net source of CO₂ to the atmosphere in the future and contributing to climate change.

Brown, Sandra. 1996. Mitigation potential of carbon dioxide emissions by management of forests in Asia. *Ambio* 25:273-78.

Substantial areas of available forest lands in Asia could be managed for C conservation and sequestration. A recent assessment of the literature by a scientist at EPA concluded that 133 Mha are potentially available for establishment of plantations and agroforests, 48 Mha of tropical lands are potentially available for natural and assisted forest regeneration, and tropical deforestation could be slowed on 33.5 Mha. The potential quantity of C conserved and sequestered on these lands was estimated to be 2050 under baseline conditions is equivalent to about 4% of the global fossil fuel emissions over the same time period. An example of a forestry project in southern China, whose main goal was to rehabilitate degraded lands by planting native pine trees and at the same time provide biomass fuel for the local rural inhabitants was used to demonstrate that C sequestration, and thus mitigation, is an added benefit to more traditional uses of forests. This forestry project is currently mitigating CO₂ emissions by an increase in C storage on the land and by substitution of fossil fuels with biomass fuel (about 1.4 Mg C ha⁻¹ yr⁻¹). With a change in management an almost two-fold increase in the current reduction of net C emissions would occur. Assuming that these rates of C sequestration occur on all the 2.5 Mha of reforested land, the total C sequestered would amount to 7 Tg/yr. To put this amount into perspective, it would take about 20 yr for a forestation program established on estimates of available land (described above) to achieve this annual rate of C sequestration. (Sandra Brown, tel: 541-754-4346).

Brown, Sandra, J. Sathaye, Melvin Cannell and P. Kauppi. 1996. Management of forests for mitigation of greenhouse gas emissions. *In* Climate Change 1995. Robert T. Watson, Marufu C. Zinyowera and Richard H. Moss, editors. Ch 24:773-797.

Three categories of promising forestry practices that promote sustainable management of forests and at the same time conserve and sequester carbon (C) are considered in this chapter: (1) management for conservation of existing C pools in forests by slowing deforestation, changing harvesting regimes, and protecting forests from other anthropogenic disturbances; (2) management for expanding C storage by increasing the area and/or C density in native forests, plantations, and agroforestry and/or in wood products; and (3) management for substitution by increasing the transfer

of forest biomass C into products such as biofuels and long-lived wood products that can be used instead of fossil-fuel based products. Since the 1992 assessment, significant new information has been developed that improves estimates of the quantities of C that can be conserved or sequestered-and the associated implementation costs of forest sector mitigation strategies and better identifies limits to the amount of lands available for such mitigation strategies.

Brown, Sandra, Jayant Sathaye, Melvin Cannell, and Pekka E. Kauppi. 1996. Mitigation of carbon emissions to the atmosphere by forest management. Commonwealth Forestry Review 75:80-91.

There is substantial potential for forests to mitigate CO₂ emissions through several promising practices that promote sustainable management of forests and at the same time conserve and sequester C. A scientist at EPA has led an international team in reviewing and synthesizing new information on this issue to develop a global assessment of the magnitude of potential amount of carbon that can be sequestered and conserved by forest management. Forests can be managed for (1) conservation of existing C pools through slowing deforestation, changing harvesting regimes, and protecting forests from disturbances; (2) expanding C storage by increasing the area and/or C density in native forests, plantations, and agroforestry and/or in wood products; and (3) increasing the transfer of forest biomass C into products, such as biofuels and long-lived wood products, that can be substituted for fossil-fuel based products. Under baseline conditions of today's climate, the cumulative amount of C that could potentially be conserved and sequestered over the period 1995-2050 by slowing deforestation by 138 Mha (million ha) and promoting natural forest regeneration on 217 Mha in the tropics combined with the global establishment of 345 Mha of plantations and agroforestry would be about 60 to 87 Pg (Pg = 10¹⁵g), equivalent to 11-15% of the projected cumulative fossil fuel C emissions over the same period. If the wood produced from the plantation program was substituted for fossil fuels, about another 30 Pg of C would be sequestered. The cumulative cost, excluding land costs and other transaction costs, to conserve and sequester the above amounts of C range from US\$247 billion to \$302 billion. Under a changed climate and human demographics, the carbon conservation and sequestration potential would be less than that estimated under baseline conditions because land would be less available in the tropics, and available lands would remain relatively constant in the temperate and boreal regions.

Brown, Sandra L., and Paul Schroeder. 1999. Spatial patterns of aboveground production and mortality of woody biomass for Eastern U.S. forests. Ecological Applications 9:968-980.

The present and potential future role of forests in national C budgets is largely a result of past and present use and disturbance regimes of forest lands. In the eastern US there has been a long history of forest clearing and disturbance, and virtually all of the forests there have been altered to some degree at some time in the past. The

current resulting forest landscape is dominated by forests at different stages of recovery and with different C budgets. Scientists at NHEERL-WED developed maps of biomass increment and mortality for forests of the eastern U.S. based on data collected from an extensive network of remeasured plots by the USDA Forest Service Forest Inventory and Analysis unit (FIA) to determine how major components of forest carbon budgets vary across the region. Forest wood volume inventory data for net annual growth, annual mortality, and annual removals by harvest were converted to units of aboveground biomass at the county level (about 2000 counties) for 27 eastern states for hardwood and softwood forest types. Biomass increment for hardwood forests ranged from 0 to >30 Mg ha⁻¹ yr⁻¹ and averaged 8.3 Mg ha⁻¹ yr⁻¹. It was highest mostly along an arc from southern Virginia to Louisiana and east Texas. Biomass increment for softwood forests was generally lower than for hardwoods, ranging from 0 to 31 Mg ha⁻¹ yr⁻¹ with an average of 7.4 Mg ha⁻¹ yr⁻¹. The spatial pattern of biomass increment for softwood forests was similar to that for hardwoods, but softwood forests were less extensive. Spatial patterns for mortality were less pronounced for both hardwood and softwood forests. For hardwood forests, mortality ranged from 0 to 15 Mg ha⁻¹ yr⁻¹ and averaged 1.1 Mg ha⁻¹ yr⁻¹. The average mortality for softwood forests was 0.6 Mg ha⁻¹ yr⁻¹ with a range of 0 to 10 Mg ha⁻¹ yr⁻¹. The rate of mortality on a biomass basis averaged <1%/yr for both hardwood and softwood forests. A first-order C budget based on our results (biomass increment minus mortality, adjusted for decomposition, minus harvest, adjusted for slash and amount going into long term products) show that eastern US forests accumulated about 416 Tg C/yr during the late 1980s to early 1990s.

Brown, Sandra L., Paul Schroeder, and Jeffrey S. Kern. 1999. Spatial distribution of biomass in forests of the Eastern USA. *Forest Ecology and Management* 123:81-90.

Forests play an important role in regional and global carbon cycles because they store massive quantities of carbon in vegetation and soil, exchange carbon with the atmosphere through photosynthesis and respiration, are sources of atmospheric carbon when they are disturbed by human or natural causes, become atmospheric sinks during regrowth, and can be managed to sequester or conserve significant quantities of carbon on the land. Forest biomass is a function of its successional state; direct human activities such as silviculture, and harvesting; natural disturbances caused by wildfire or pest outbreaks; and changes in climate and atmospheric pollutants. Biomass is, also, a useful measure for assessing changes in forest structure and for comparing the status and trends of forest ecosystems across a wide range of environmental conditions. Scientists at WED have produced a map of the biomass density and pools of all forests of the eastern US (33 states) using new approaches for converting inventoried wood volume to estimates of above and belowground biomass. They estimated aboveground and belowground biomass density and pools at the county level by forest type and stand size-class, and mapped the results in a geographic information system. Total biomass density for hardwood forests ranged from 36-344

Mg ha⁻¹, and for softwood forests it ranged from 2-346 Mg ha⁻¹. The total biomass for all eastern forests for the late 1980s was estimated at 20.5 Pg, 80% of which was in hardwood forests. Highest amounts of forest biomass were located in the Northern Lake states, the Appalachians, and parts of New England, and lowest amounts in the Midwestern states. The maps not only provide a vivid visual representation of the pattern of forest biomass densities and pools over space that are useful for forest managers and decision makers, but they also serve as a data base for verification of vegetation models.

Cairns, M.A., J.R. Barker, R.W. Shea and P.K. Haggerty. 1996. Carbon dynamics of Mexican tropical evergreen forests: influence of forestry mitigation options and refinement of carbon-flux estimates. *Interciencia* 21:216-223.

The global carbon (C) cycle has become an important topic in scientific research (Houghton et al., 1992). This emphasis has emerged from two sources. First is the increased atmospheric concentrations of CO₂ since 1880 (from 280 ppmv to 356 ppmv), heightening the concern about global warming. Second is the signing of the UN framework Convention on Climate Change, pledging signatory nations to account for an stabilize their greenhouse gas emissions. Scientists have increasingly focused on the roles of changes in land cover, land use, and land management in regulating C flux, or movement of carbon, between the terrestrial biosphere and the atmosphere (Schimel, 1995). Two principal concerns in C-flux research involve balancing the global C cycle (Watson et al., 1992) and mitigating atmospheric CO₂ buildup by reducing sources and enhancing sinks (Houghton et al., 1992; Trexler and Haugen, 1995). More accurate accounting of forest biomass densities and improved areal estimates are two promising approaches to reduce uncertainty in the global C budget (Brown and Lugo, 1992; Dixon et al., 1994; Schimel et al., 1995). Increased management of tropical forests has been proposed to aid mitigation of biogenic CO₂ flux (MCAPCC, 1990; Myers, 1990; Sedjo, 1989).

Cairns, Michael A., Sandra Brown, Eileen H. Helmer, and Greg A. Baumgardner. 1997. Root biomass allocation in the world's forests. *Oecologia* 111:1-11.

Because the world's forests play a major role in regulating nutrient and carbon cycles, there is much interest in estimating their biomass. Estimates of aboveground biomass based on well-established methods are relatively abundant; estimates of root biomass based on standard methods are much less common. Our work determined if a reliable method to estimate root biomass density for forests could be developed based on existing data. Relationships between both root biomass density (Mg ha⁻¹) and root:shoot ratios (R/S) as dependent variables and various edaphic and climatic

independent variables were tested. None of the independent variables of aboveground biomass density, latitude, temperature, precipitation, temperature:precipitation ratios, tree type, soil texture, and age had explanatory value for R/S. However, aboveground biomass density, age, and latitudinal category, in that order, were the most important predictors of root biomass density, and together explained 85% of the variation. A comparison of root biomass density estimates based on our equations with those based on use of generalized R/S ratios for forests in tropical Asia and the U.S. indicated that our method tended to produce higher estimates.

Cairns, Michael A., Rodolfo Dirzo and Frank Zadroga. 1995. Forests of Mexico. *Journal of Forestry* 93:21-24.

Forests of Mexico as elsewhere provide essential goods and services for both local citizens and the international community. Such benefits include climate regulation, biodiversity, and wood and nonwood products for local consumption and economic activity (Cairns and Meganck 1994). Deforestation, therefore, is a matter of great environmental and economic concern. This article assesses rates of deforestation, the present status of forests in Mexico, and major factors responsible for deforestation in the eight-state tropical southeastern region.

Approximately 26 percent of Mexico's 191 million hectare (ha) land area, or 49.7 million ha, is covered with closed forests (Masera et al. 1992). However, estimates range from 44.2 million ha (Flores Villela and Gérez 1988) to 61.8 million ha (SARH 1986). From 18 million ha (CNIF 1991) to 24 million ha (SARH 1992) are considered disturbed, usually as a result of shifting cultivation. Together with its highly diverse climate, topography, and geology, Mexico's location at the juncture of the holarctic and neotropical biogeographical zones results in a high degree of biological diversity. To protect the forests and their diversity, 5 million ha are relatively well preserved by the government, with 57 percent of protected areas in open forests and woodlands and 34 percent in tropical evergreen forests (Ordóñez 1990).

Such knowledge of the extent of forest types and other land-cover classes is essential in allocating natural area conservation status for biodiversity protection. This information, as well as rates of deforestation, is needed to measure the effects of deforestation, such as greenhouse gas emissions.

Cairns, Michael A., Patricia K. Haggerty, Roman Alvarez, B. H. J. De Jong, and Ingrid Olmsted. 2000. Tropical Mexico's recent land-use and land-cover change: a region's contribution to the global carbon cycle. *Ecological Applications* 10:1426-1441.

We applied modeled biomass density estimates to changes in land use/land cover (LU/LC) statistics for an intensively impacted and highly fragmented landscape in tropical Mexico to estimate the flux of C between terrestrial ecosystems and the atmosphere between 1977 and 1992. Biomass densities were assigned to hybrid LU/LC classes on vegetation maps produced by Mexican governmental organizations and, by differencing areas and biomass carbon (C) pools, net C flux was calculated in the eight-state tropical region of southeast Mexico. Tropical Mexico experienced a mean annual deforestation rate of more than 569,000 ha yr⁻¹, or 2.2%, between 1977 and 1992. The total area of closed forests decreased by 27%, open/fragmented forests by 31%, and agroecosystem areas increased by 64%. Total mean biomass densities ranged from a high of 265 Mg ha⁻¹ in the Veracruz state tall/medium tropical evergreen forest class to a low of 12 Mg ha⁻¹ in the cultivated land class (several states). We estimate that a total of 289 TgC were released from the terrestrial biosphere during the 15-year period covered by our study, equal to approximately 20% of the region's 1977 biomass C pool. The study region, while comprising just 24% of Mexico's surface area, contributed 37% of the net national C emissions from LU/LC change.

Cairns, Michael A., Wei Min Hao, Ernesto Alvarado, and Patricia K. Haggerty. Carbon emissions from Spring 1998 fires in Tropical Mexico. *Proceedings of International Conference on Tropical Forests and Climate Change: Status, Issues and Challenges.*, October 19-22, 1998 in Manila, Philippines.

We used NOAA-AVHRR satellite imagery, biomass density maps, fuel consumption estimates, and a carbon emission factor to estimate the total carbon (C) emissions from the Spring 1998 fires in tropical Mexico. All eight states in southeast Mexico were affected by the wildfires, although the activity was concentrated near the common border of Oaxaca, Chiapas, and Veracruz. The fires burned approximately 482,000 ha and the land use/land cover classes most extensively impacted were the tall/medium selvas (tropical evergreen forests), open/fragmented forests, and perturbed areas. The total prompt emissions were 4.6 TgC during the two-month period of our study, contributing an additional 24% to the region's average annual net C emissions from forestry and land-use change. Mexico in 1998 experienced its driest Spring since 1941, setting the stage for the widespread burning. If fire episodes such as the one that occurred in Mexico and around the world become the norm due to warmer and drier conditions, then an increase in C emissions may represent a significant positive feedback to global climate change.

Cairns, Michael A. and Richard A. Meganck. 1994. Carbon sequestration, biological diversity, and sustainable development: Integrated forest management. *Environmental Management* 18:13-22.

Tropical deforestation provides a significant contribution to anthropogenic increases in atmospheric CO₂ concentration that may lead to global warming. Forestation and other forest management options to sequester CO₂ in the tropical latitudes may fail unless they address local economic, social, environmental, and political needs of people in the developing world. Forest management is discussed in terms of three objectives: carbon sequestration, sustainable development, and biodiversity conservation. An integrated forest management strategy of land-use planning is proposed to achieve these objectives and is centered around: preservation of primary forest, intensified use of nontimber resources, agroforestry, and selective use of plantation forestry.

Cairns, M.A., I. Olmsted, J. Granados, J. Argaez. 2003. Composition and Aboveground Tree Biomass of a Dry Semi-Evergreen Forest on Mexico's Yucatan Peninsula. *Forest Ecology and Management* 186: 125-132.

Forest biomass estimates are used to help quantify pools and flux of greenhouse gases (e.g., CO₂-C) from the terrestrial biosphere to the atmosphere associated with land-use and land-cover changes. Such estimates based on direct measurements are quite limited for tropical dry forests. The goal of this study was to assess the species composition and biomass density in an intact Mexican forest representative of the tropical dry forest biome. We then compared our measured biomass with biomass estimates computed with a published model in current use. A total of 72 species were found in a 0.5-ha stand with a basal area of 31.3 m² ha⁻¹. The dominant species, in terms of biomass, were Brosimum alicastrum, Manilkara zapota, Luehea speciosa, Pouteria unilocularis, Trichilia minutiflora, and Spondias mombin. Tree heights ranged up to 30 m and dbh to 82.1 cm. Species-specific biomass regression models were developed for the six most common species of large (>10 cm dbh) trees and for the nine most common species of small (<10 cm dbh) trees from the destructive harvest of 698 trees. Mass of large trees (n = 195) were used to derive the regression model $Y = \exp\{-2.173 + 0.868 \ln(D^2 \cdot TH) + 0.0939/2\}$, where Y = total dry weight (kg), D = dbh (cm), and TH = total height (m). Total aboveground tree biomass was estimated to be 225 Mg ha⁻¹, and was dominated (85%) by the biomass of the large trees. The actual biomass of each of the 195 large trees was compared to individual tree biomass calculated with a published regression model (Brown 1997) that is based on measurements of 29 trees. We found that the published model underestimated biomass of these trees by 31% (37.6 vs. 54.4 Mg). Calculated biomass was less than measured biomass for 29 of 33 species. The current study points to the value of site-specific assessment of aboveground biomass and may contribute to more accurate estimates of dry tropical forest biomass densities currently used to estimate greenhouse gas flux from land management activity.

Cairns, Michael A., Jack K. Winjum, Donald L. Phillips, Tatyana P. Kolchugina and Ted S. Vinson. 1997. Terrestrial carbon dynamics: case

studies in the former Soviet Union, the conterminous United States, Mexico and Brazil. Mitigation and Adaptation Strategies for Global Change 1:363-383.

This research assessed land-use impacts on C flux at a national level in four countries: former Soviet Union, United States, Mexico and Brazil, including biotic processes in terrestrial ecosystems (closed forests, woodlands, and croplands), harvest of trees for wood and paper products, and direct C emission from fires. The terrestrial ecosystems of the four countries contain approximately 40% of the world's terrestrial biosphere C pool, with the FSU alone having 27% of the global total. Average phytomass C densities decreased from south to north while average soil C densities in all three vegetation types generally increased from south to north. The C flux from land cover conversion was divided into a biotic component and a land-use component. We estimate that the total net biotic flux (Tg/yr) was positive (= uptake) in the FSU (631) and the U.S. (332), but negative in Mexico (-37) and Brazil (-16). In contrast, total flux from land use was negative (= emissions) in all four countries (TgC/yr): FSU -342; U.S. -243; Mexico -35; and Brazil -235. The total net effect of the biotic and land-use factors was a C sink in the FSU and the U.S. and a C source in both Brazil and Mexico.

De Jong, B.H.J., M.A. Cairns, P.K. Haggerty, N. Ramirez-Marcial, S. Ochoa-Gaona, J. Mendoza-Vega, M. Gonzalez-Espinosa, and I. March-Mifsut. 1999. Land-use change and carbon flux between the 1970s and 1990s in central highlands of Chiapas, Mexico. Environmental Management 23:373-385.

In an article submitted to Environmental Management, WED scientists presented results of a study in an intensively impacted and highly fragmented landscape in which they applied field-measured carbon (C) density values to land use/land cover (LU/LC) statistics to estimate the flux of C between terrestrial ecosystems and the atmosphere from the 1970s and 1990s. Carbon densities were assigned to common LU/LC classes on vegetation maps produced by Mexican governmental organizations and, by differencing areas and C pools, net C flux was calculated for the central highlands of Chiapas, Mexico during a 16-year period. The total area of closed forests was reduced by half while degraded and fragmented forests expanded 56% and cultivated land and pasture areas increased by 8% and 30%, respectively. Total mean C densities ranged from a high of 430 MgC ha⁻¹ in the oak and evergreen cloud forests class to a low of 140 MgC ha⁻¹ in the pasture class. The differences in total C densities among the various LU/LC classes were due to changes in biomass while soil organic matter C remained similar. They estimated that a total of 17.54 TgC were released to the atmosphere during the period of time covered by the study, equal to approximately 34% of the 1975 vegetation C pool. The Chiapas highlands, while comprising just 0.3% of Mexico's surface area, contributed 3% of the net national C emissions.

De Jong, Ben H. J., Susana Ochoa-Gaona, Miguel Angel Castillo-Santiago, Neptali Ramirex-Marcial, and Michael A. Cairns. 2000. Carbon flux and

patterns of land-use/land-cover change in the Selva Lacandona, Mexico. *Ambio*, 503-511.

Based on land-use/land-cover (LU/LC) maps and satellite imagery, a WED scientist and Mexican colleagues have estimated LU/LC change and associated C fluxes in three sub-regions of the Selva Lacandona, Chiapas, Mexico between 1976 and 1996. The total area of closed tropical rainforest was reduced by 31%, while secondary forests expanded more than nine-fold, secondary shrubs by nearly six-fold, and cultivated land and pasture areas expanded 21% and 92%, respectively. However, the LU/LC change was not uniformly distributed over the entire study area. Total mean C densities ranged from 452 MgC ha⁻¹ for closed mature forests to a low of 120 MgC ha⁻¹ for pasture. The heavily converted areas lost an estimated 24% of their total 1976 C pools, whereas the lightly impacted region lost only 3%. The Selva Lacandona region, while comprising just 0.3% of Mexico's surface area, contributed 6% of the net national LU/LC C emissions during this recent 20-year period.

Delaney, Matt, Sandra Brown, Ariel Lugo, Armando Torres-Lezama, and Narsizo Bello Quintero. 1997. The distribution of organic carbon in major components of forests located in six life zones of Venezuela. *Journal of Tropical Ecology* 13:697-708.

One of the major uncertainties concerning the role of tropical forests in the global carbon cycle is the lack of adequate data on the carbon content of all their components. This lack of knowledge prevents scientists from reaching consensus on how changes in land use and land management influence the exchange of carbon dioxide between the atmosphere and terrestrial ecosystems. Research by a scientist at the EPA, with colleagues from Illinois, Puerto Rico and Venezuela, contributed to filling this data gap by estimating environments. Most C was in the soil (125 to 342 Mg ha⁻¹) and aboveground biomass (8 to 179 Mg ha⁻¹). The C in fine litter (1.1 to 5.2 Mg ha⁻¹), dead wood (1.2 to 21.2 Mg ha⁻¹) and roots (3.5 to 39.3 Mg ha⁻¹) accounted for less than 10 % of the total C density. Total amount of C among life zones ranged from 311 to 488 Mg ha⁻¹, and showed no clear trend with life zone. In four of the six life zones, more C was found in the dead (soil, litter, dead wood) than in the live (tree biomass and roots) components (live to dead ratios of 0.03 to 0.76); the lowland moist and moist transition to dry life zones had live to dead ratios greater than one. Results from this research suggest that for most life zones, an amount equivalent to between 26 and 59 % of the aboveground biomass is located in roots and necromass. These percentages coupled with reliable estimates of aboveground biomass from forest inventories enable a more complete and reliable estimation of the C content of tropical forests to be made, and thus more reliable estimates of the magnitude of the C fluxes to and from the land during deforestation and regrowth.

Delaney, Matt, Sandra Brown, Ariel E. Lugo, Armando Torres-Lezama, and Narsizo Bello Quintero. 1998. The quantity and turnover of dead wood in permanent forest plots in six life zones of Venezuela. *Biotropica*, 30:2-11.

Dead wood is recognized as potentially an important component in forest ecosystems because it can represent a significant quantity of the forest's carbon pool. A scientist at EPA and colleagues measured the quantity of dead wood (lying and standing dead) in 27 long-term (up to 30 yr) permanent forest plots located in six different life zones of Venezuela. Dead wood was separated into fine (< 10 cm in diameter) and coarse (> 10 cm in diameter) classes, and one of three decomposition states: sound, intermediate, or rotten. The total quantity of dead wood, averaged by life zone, was lowest in the dry (2.43 Mg ha⁻¹), reached a peak in the moist (42.33 Mg ha⁻¹) and decreased slightly in the wet (34.50 Mg ha⁻¹) life zone. The majority of dead wood was found in the large and standing dead diameter classes (77 % to 97 % of the total). The decomposition state of dead wood in all plots was mostly rotten (45%) or intermediate (44 %); there was very little sound wood (11%). Turnover time of dead wood was fastest in the moist transition to dry zone (average of 1.30 yr⁻¹), followed by the lower montane moist zone (average of 0.13 yr⁻¹), and the moist forest zone (average of 0.09 yr⁻¹). The amount of aboveground biomass represented by dead wood ranged from 5 to 20 %, indicating that dead wood represents a significant amount of carbon in these tropical forests.

Dixon, Robert K. Regional forest management planning in the southern United States. *In* North American Conference on Forests and Climate Change: Climate Institute.

Simulation models have been employed to examine the effects of global climate change on forest ecosystems in the southern United States. Predictions for this region suggest a warmer climate in the next century. Shifts in forest species distribution and composition are projected in response to climate change within the next 50-80 years. A long-term decline in forest productivity could occur and timber production, biotic habitat, water quality and quantity from watersheds, soil properties, and recreation opportunities could be altered. Forest management planning by industry, non-industrial private landowners and public agencies will be influenced by climate change impacts. Forest regeneration practices, silvicultural treatments and rotation lengths in natural and managed forests may need to be adjusted to cope with climate change. An increase in risk associated with climate change events will likely influence investment decisions regarding intensive forest management by owners and managers. Public policy responses to climate change can influence forest management planning for public and private lands in the southern United States. Financial incentives and greater regulation of forest practices could be employed to stimulate sustained forest productivity. Given the uncertainty of climate change predictions and the long-lived nature of forests,

management planning strategies may require consideration of both adaptive and mitigative responses.

Dixon, Robert K. 1990. Responses and feedbacks of global forests to climate change. Presented at the Symposium on Management and Productivity of Western-Montane Forest Soils, Boise, ID, April 10-12.

The accumulation of greenhouse gases in the atmosphere over the past century is projected to cause a warming of the Earth. Climate change predictions vary by region and terrestrial biosphere response and feedbacks will be ecosystem specific. Forests play a major role in the Earth's carbon cycle through assimilation of CO₂ storage of carbon, and emission of greenhouse gases. Simulation models have been employed to examine the possible responses to climate change of global forest ecosystems. Major shifts in forest species distribution and composition are predicted in response to projected climate change within the next 50-80 years. The range of some species is expected to shift dramatically in biomes worldwide. Savanna type vegetation could replace some forests under the more extreme climate change predictions in temperate latitudes. The ultimate response and feedbacks of forests will be influenced by the direction and magnitude of climate change, site quality and other stress agents. Establishment of new forests and implementation of management practices could potentially be used to sequester significant amounts of atmospheric CO₂. Preliminary evidence suggests the terrestrial biosphere could be managed to reduce accumulation of greenhouse gases in the atmosphere and mitigate negative impacts of climate change.

Dixon, R.K., K.J. Andrasko, F.G. Sussman, M.A. Lavinson, M.C. Trexler and T.S. Vinson. 1993. Forest sector carbon offset projects: near-term opportunities to mitigate greenhouse gas emissions. *Water, Air, and Soil Pollution* 70:561-577.

The Framework Convention on Climate Change separately recognizes sources and sinks of greenhouse gases and provides incentives to establish C Offset projects to help meet the goal of stabilizing emissions. Forest systems provide multiple opportunities to offset or stabilize greenhouse emissions through a reduction in deforestation (C sources), expansion of existing forests (CO₂ sinks) or production of biofuels (offset fossil fuel combustion). Attributes and dimensions of eight forest-sector C offset projects established over the past three years, were examined. The projects, mostly established or sponsored by US or European electric utilities, propose to conserve/sequester over 30 x 10⁶ Mg C in forest systems at an initial cost of \$1 to 30 Mg C. Given the relative novelty and complexity of forest sector C offset projects, a number of biogeochemical, institutional, socioeconomic, monitoring, and regulatory issues merit analysis before the long-term potential and cost effectiveness of this greenhouse gas stabilization approach can be determined.

Dixon, Robert K. 1992. Global carbon cycle and climate change - an overview. In The Science of Global Change - The Impact of Human Activities on the Environment. David A. Dunnette and Robert J. O'Brien, editors. American Chemical Society, Washington DC. Pp375-378.

The production of greenhouse gases by anthropogenic activities may have begun to change the global climate. Although the global carbon cycle plays a significant role in projected climate change, considerable uncertainty exists regarding pools and fluxes within this cycle. Given our present understanding of global carbon sources and sinks, feedbacks from the biosphere will influence the process of climate change. Opportunities may exist to manage the biosphere and reduce the accumulation of greenhouse gases in the atmosphere. The four chapters in this section survey the role of the global carbon cycle in projected climate change.

Dixon, R.K., S. Brown, R.A. Houghton, A.M. Solomon, M.C. Trexler and J. Wisniewski. 1994. Carbon pools and flux of global forest ecosystems. Science 263:185-190.

Forest systems cover more than 4.1×10^9 hectares of the Earth's land area. Globally, forest vegetation and soils contain about 1146 petagrams of carbon, with approximately 37 percent of this carbon in low-latitude forests, 14 percent in mid-latitudes, and 49 percent at high latitudes. Over two-thirds of the carbon in forest ecosystems is contained in soils and associated peat deposits. In 1990, deforestation in the low latitudes emitted 1.6 ± 0.4 petagrams of carbon per year, whereas forest area expansion and growth in mid- and high-latitude forest sequestered 0.7 ± 0.2 petagrams of carbon per year, for a net flux to the atmosphere of 0.9 (0.4 petagrams of carbon per year). Slowing deforestation, combined with an increase in forestation and other management measures to improve forest ecosystem productivity, could conserve or sequester significant quantities of carbon. Future forest carbon cycling trends attributable to losses and regrowth associated with global climate and land-use change are uncertain. Model projections and some results suggest that forests could be carbon sinks or sources in the future.

Dixon, Robert K. and Olga N. Krankina. 1993. Forest fires in Russia: carbon dioxide emissions to the atmosphere. Can. J. For. Res. 23:700-705.

Boreal forests of Russia play a prominent role in the global carbon cycle and the flux of greenhouse gases to the atmosphere. Large areas of Russian forest burn annually, and contributions to the net flux of carbon to the atmosphere may be significant. Forest fire emissions were calculated for the years 1971-1991 using fire frequency and distribution data and fuel and carbon density for different forest

ecoregions of Russia. Both direct carbon release and indirect post-fire biogenic carbon flux were estimated. From 1971 to 1991 the annual total forest area burned by wildfire ranged from 1.41×10^6 to 10.0×10^6 ha. Approximately 15 000 - 25 000 forest fires occurred annually during this period. Mean annual direct CO₂-C emissions from wildfire was approximately 0.05 Pg over this 21 -year period. Total post-fire biogenic CO₂-C emissions for 1971-1991 ranged from 2.5 to 5.9 Pg (0.12-0.28 Pg annually). Forest fires and other disturbances are expected to be a primary mechanism driving vegetation change associated with projected global climate change. Future forest fire scenarios in Russia based on general circulation model projections suggest that up to 30-50% of the land surface area, or 334×10^6 to 631×10^6 ha of forest, will be affected. An additional 6.7×10^6 to 12.6×10^6 ha of Russian boreal forest are projected to burn annually if general circulation model based vegetation-change scenarios are achieved within the next 50 years. The direct flux of CO₂-C from future forest fires is estimated to total 6.1-10.7 Pg over a 50-year period. Indirect post-fire biogenic release of greenhouse gases in the future is expected to be two to six times greater than direct emissions. Forest management and fire-control activities may help reduce wildfire severity and mitigate the associated pulse of greenhouse gases into the atmosphere.

Dixon, Robert K., Paul E. Schroeder, Jack K. Winjum. 1991. Assessment of Promising Forest Management Practices and Technologies for Enhancing the Conservation and Sequestration of Atmospheric Carbon and Their Costs at the Site Level. US EPA Report EPA/600/3-91/067.

The accumulation of greenhouse gases in the atmosphere, particularly CO₂ is projected to alter the earth's climate. The response and feedbacks of forest systems to climate change are expected to be significant. Forest systems are prominent in the global carbon cycle through photosynthetic uptake of CO₂ and release by respiration and decay of organic residues. This forest carbon cycle accounts for over 90 Gt of annual carbon flux out of a total of 110 Gt annually for all terrestrial ecosystems. The global carbon content of forest systems, above and below ground, is about 1400 Gt within a worldwide terrestrial pool of about 2200 Gt.

Prior reports suggest managed forest and agroforestry systems have the potential to sequester and conserve up to 10 Gt of carbon annually in the terrestrial biosphere. Management of forest and agroforestry systems could help reduce the accumulation of carbon in the atmosphere while continuing to provide needed goods and services for people, especially in tropical nations. Uncertainties include: 1) estimates of carbon cycling and biogeochemistry in boreal, temperate, and tropical forests; and 2) the social, political, and economic acceptance of these managed systems in the world at significantly increasing levels of use.

The international community, however, recognizing the prominent role of forest biomes in global ecology and the global carbon cycle, has agreed to promulgate a Global Forest Agreement (GFA) by 1992. The proposed Global Forest Agreement and earlier international agreements such as the 1989 Noordwijk Ministerial Declaration, have

identified global forest management goals to: slow deforestation; stimulate sustained forest management and productivity; protect biodiversity; and reduce environmental threats to world forests. The appropriate mix of technical options, however, to manage global forests for these goals have yet to be identified.

The objectives of this report are to assess and synthesize current knowledge on three policy-science topics:

1. Identify promising technologies and practices that could be utilized at technically suitable sites in the world to manage forests and agroforestry systems for sequestering and conserving carbon.
2. Assess available data on costs at the site level for promising forest and agroforestry management practices.
3. Evaluate estimates of land technically suitable in forested nations and biomes of the world to help meet the Noordwijk forestation targets and the proposed Global Forest Agreement goals.

Dixon, Robert K., Joel B. Smith, Sandra Brown, Omar Masera, Luis J. Mata and Igor Buksha. 1999. Simulations of forest system response and feedbacks to global change: experiences and results from the U.S. Country Studies Program. Ecological Modeling 122:289-305.

Large shifts in the response and feedbacks of forest systems are implied by models and systems analysis driven by global change scenarios of general circulation models (GCMs). Prior climate change analyses and modeling efforts have been reported at a global scale in a few developed countries, but relatively few national assessments have been successfully completed in developing countries. Under the auspices of the U.S. Country Studies Program, analysts from 55 countries employed a common set of methods and models to characterize current carbon (C) pools in forests, future impacts of global change on forest distribution, and management options for conserving and sequestering carbon dioxide (CO₂) in forest systems. The analysis revealed that the response and feedbacks of forest systems to global climate change will be profound in the 55 countries studied on five continents. Globally, forest vegetation and soils contain about 1146 Pg C, with approximately 37% of this C in low-latitude forests, 14% in mid-latitudes, and 49% at high latitudes. The impacts of future global change on forest distribution and productivity will be most significant at high latitudes, with more modest changes in distribution and productivity at low latitudes. Future opportunities to conserve and sequester CO₂ in forest systems are potentially significant, but land-use practices and global change will influence the size of this C pool and CO₂ sink. In the future, a greater proportion of forests at all latitudes could become a greenhouse gas (GHG) source if sustained management and conservation policies are not employed. The timing and magnitude of future changes in forest systems are

dependent on global environmental factors (for example, global change, biogeochemical Sulphur and Nitrogen cycles), as well as on human factors such as demographics, economic growth, technology, and resource management policies.

Dixon, R.K., D.P. Turner. 1991. The global carbon cycle and climate change: responses and feedbacks from below-ground systems. *Environmental Pollution* 73:245-262.

According to most global climate models, a continued build-up of CO₂ and other greenhouse gases will lead to significant changes in temperature and precipitation patterns over large parts of the Earth. Below-ground processes will strongly influence the response of the biosphere to climate change and are likely to contribute to positive or negative biospheric feedbacks to climate change. Current global carbon budgets suggest that as much as 2000 Pg of carbon exists in soil systems. There is considerable disagreement, however, over pool sizes and flux (e.g. CO₂, CH₄) for various ecosystems. An equilibrium analysis of changes in global below-ground carbon storage due to a doubled-CO₂ climate suggests a range from a possible sink of 41 Pg to a possible source of 101 Pg. Components of the terrestrial biosphere could be managed to sequester or conserve carbon and mitigate accumulation of greenhouse gases in the atmosphere.

Dixon, Robert K., Jack K. Winjum, Kenneth J. Andrasko, Jeffrey J. Lee and Paul E. Schroeder. 1994. Integrating land-use systems: assessment of promising agroforest and alternative land-use practices to enhance carbon conservation and sequestration. *Climatic Change* 27:71-92.

Degraded or sub-standard soils and marginal lands occupy a significant proportion of boreal, temperate and tropical biomes. Management of these lands with a wide range of existing, site-specific, integrated, agroforest systems represents a significant global opportunity to reduce the accumulation of greenhouse gases in the atmosphere. Establishment of extensive agricultural, agroforest, and alternative land-use systems on marginal or degraded lands could sequester 0.82-2.2 Pg carbon (C) per year, globally, over a 50-year time-frame. Moreover, slowing soil degradation by alternative grassland management and by impeding desertification could conserve up to 0.5-1.5 Pg C annually. A global analysis of biologic and economic data from 94 nations representing diverse climatic and edaphic conditions reveals a range of integrated land-use systems which could be used to establish and manage vegetation on marginal or degraded lands. Promising land-use systems and practices identified to conserve and temporarily store C include agroforestry systems, fuelwood and fiber plantations, bioreserves, intercropping systems, and shelterbelts/windbreaks. For example, successful establishment of low-intensity agroforestry systems can store up to 70 Mg

C/ha in boreal, temperate and tropical ecoregions. The mean initial cost of soil rehabilitation and revegetation ranges from \$500-3,000/ha for the 94 nations surveyed. Natural regeneration of woody vegetation or agro-forestation establishment costs were less than \$1000/ha in temperate and tropical regions. The costs of C sequestration in soil and vegetation systems range from \$1-69/Mg C, which compares favorably with other options to reduce greenhouse gas emissions to the atmosphere. Although agroforestry system projects were recently established to conserve and sequester C in Guatemala and Malaysia, constraints to wide-spread implementation include social conditions (demographic factors, land tenure issues, market conditions, lack of infrastructure), economic obstacles (difficulty of demonstrating benefits of alternative systems, capital requirements, lack of financial incentives) and, ecologic considerations (limited knowledge of impacts and sustainability of some systems).

Dixon, Robert K., Jack K. Winjum and Paul E. Schroeder. 1993. Conservation and sequestration of carbon - The potential of forest and agroforest management practices. Global Environmental Change June:159-173.

Forests play a major role in Earth's carbon cycle through assimilation, storage, and emission of CO₂. Establishment and management of boreal, temperate, and tropical forest and agroforest systems could potentially enhance sequestration of carbon in the terrestrial biosphere. A biological and economic analysis of forest establishment and management options from 94 nations revealed that forestation, agroforestry, and silviculture could be employed to conserve and sequester one Petagram (Pg) of carbon annually over a 50-year period. The marginal cost of implementing these options to sequester 55 Pg of carbon would be approximately \$10/Mg.

King, George A. 1993. Conceptual approaches for incorporating climatic change into the development of forest management options for sequestering carbon. *Climate Research* 3:61-78.

The potential for significant environmental change over the next 100 yr has resulted in efforts to develop mitigation options for reducing the rate of increase of carbon dioxide concentrations in the atmosphere. One of the more promising options is management of forest and agroforestry systems. However, most assessments of the potential of forest management options to sequester carbon have not factored future environmental change (climate and CO₂ concentration) into their analyses. Climate and ecological models that could be used to incorporate environmental change into forest mitigation planning efforts are reviewed in this paper in terms of their relative strengths and limitations for this particular application. Recommendations are then made as to how to use the available models to estimate the global and regional potential for sequestering carbon in the terrestrial biosphere, incorporating future environmental change into the analyses. Recommendations are also made as to how to target the most promising regions for reforestation efforts given the likelihood of future environmental change.

Gaston, Greg G., Peggy M. Bradley, Ted S. Vinson and Tatayana P. Kolchugina. 1997. Forest Ecosystem Modeling in the Russian Far East Using Vegetation and Land-Cover Regions Identified by Classification of GVI. Photogrammetric Engineering & Remote Sensing 63:51-58.

Forest ecosystem models are an important tool for estimating carbon pools and fluxes in the terrestrial biosphere. Models can provide dynamic estimates through time and can predict the results of changes in forest management practices or changes in the forest ecosystem resulting from natural disturbances. Vegetation and landcover regions identified through unsupervised classification of Global Vegetation Index (GVI) data provide an appropriate ecosystem and species description for model input parameters. The timing and magnitude of photosynthesis as indicated by NDVI observed from four year average monthly GVI composites were used to identify 42 distinct regions of the former Soviet Union (FSU). These regions represent areas of similar vegetation and land cover at a higher level of spatial detail and with more thorough species description than provided by available continental scale thematic maps. The image classes provide a consistent framework of vegetation and land-cover information across the FSU. Qualitative comparison on a pixel-by-pixel basis with detailed topographic maps and other data showed that, in general, despite the widely acknowledged problems with GVI, surface conditions were well identified by the GVI classification. The image class descriptions for the continental scale analysis required a supplemental description of the species specific to regional ecosystems before they could be used as a forest ecosystem model input parameter. Model predictions for carbon pools in test sites located in the Amur region of Russia compared well to carbon estimates made using other techniques. While GVI-based image classes appear to be appropriate for continental scale analysis, there is still a need to validate the GVI classification approach using higher resolution remote sensing data and field investigations.

Gaston, Greg, Sandra Brown, Massimiliano Lorenzini, and K. D. Singh. 1998. State and change in carbon pools in the forest of tropical Africa. Global Change Biology 4:97-114.

There are large uncertainties associated with estimates of the CO₂ flux to the atmosphere due to changes in land use in the tropics caused by the uncertainty inherent in biomass C density estimates and in patterns and rates of land-use change as well as a general inability to link patterns of deforestation and degradation with biomass C. Significant improvements in C flux estimates will likely result from a better matching of biomass C density estimates to the forests undergoing change. Scientist at the EPA, using Africa as a case study, combined spatially explicit estimates of biomass C density of forests, obtained by modeling in a geographic information system (GIS), with new data on the distribution of vegetation and forest areas reported at subnational

units for 1980 and 1990 by the Food and Agriculture Organization (FAO). The total C pool in above and belowground biomass for all forests, woodlands/woody savannas, and grassland/shrub savannas of tropical Africa in 1980 was estimated at 50.6 Pg (1015 g). Zaire alone accounted for more than one third of this total. Forest biomass accounted for 96% of the total C pool, while grassland and shrub savannas accounted for about 4% only. The total change in the aboveground forest C pool for the decade 1980-1990 due to changes in land use, deforestation and forest degradation, was estimated to be 6.6 Pg C. Of this total, 43% was due to deforestation and 57% due to biomass reduction by other human activities. Six countries, mostly in central Africa, accounted for more than 73% of the total change in the C pool. Taking all the potential sources of error into consideration, the scientists believe that the estimates for state and change in C densities and pools in the forests of tropical Africa are conceptually correct and the best spatially explicit data available at this time.

Gaston, G.G., P.L. Jackson, T.S. Vinson, T.P. Kolchugina, M. Botch and K. Kobak. 1994. Identification of carbon quantifiable regions in the former Soviet Union using unsupervised classification of AVHRR global vegetation index images. *Int. J. Remote Sensing* 15:3199-3221.

Global Vegetation Index (GVI) data from the Advanced Very High Resolution Radiometer (AVHRR) was used to identify macro-scale vegetation land cover regions in the former Soviet Union (FSU). These regions are a better representation of surface vegetation and land cover than can be obtained from existing thematic maps of the FSU. Image classes were identified through cluster analysis using the ISODATA clustering algorithm and a maximum likelihood classifier. Qualitative analysis of the image variants produced with different input parameters indicated that an image with 42 classes best represented significant details in vegetation and land cover patterns without producing uninterpretable levels of details that represent artefacts of the clustering algorithm. Initial identification of image classes has been made by considering the weight of evidence provided by quantitative and qualitative analysis of existing maps, analytical tools from class statistics, ancillary data from a variety of sources and expert assessment by Russian scientists with extensive field experience in the FSU. Overall, this method of image classification using GVI data appears to describe accurately regions with similar vegetation and land cover across the FSU. Some questions regarding the identification of wetlands and potential problems with classification in the Russian high arctic are discussed. The products of this research will help improve carbon budget estimates of the FSU by providing accurate delineation and definition of carbon quantifiable regions.

Gaston, Greg G., Tatyana Kolchugina and Ted S. Vinson. 1993. Potential effect of no-till management on carbon in the agricultural soils of the former Soviet Union. *Agriculture, Ecosystems and Environment* 45:295-309

Agricultural soils act as both a source and a sink for atmospheric carbon. Since the onset of cultivation, the 211.5 million ha of agricultural soils in the former Soviet Union (FSU) have lost 10.2 Gt of carbon. No-till management represents a promising option to increase the amount of carbon sequestered in the agricultural soil of the FSU. No-till management reduces erosion and sequesters additional carbon in the soil by lowering the soil temperature and raising soil moisture.

To determine the carbon sequestered under no-till management, a data base containing precultivation estimates of soil carbon for the seven major classes of soil found in the agricultural areas of the FSU was used to establish an equilibrium carbon content for each soil. Other published data provided a method to quantify the change in soil carbon brought about by converting to no-till management. Soils suitable for no-till management were analyzed and estimates of changes in carbon storage were made.

No-till management is not suitable in areas where crop production is limited by cold, wet soils. Based on the results of a geographic information system analysis using maps of climatic factors and soil characteristics, 181 million ha in the FSU were identified as climatically suitable for no-till management (almost 86% of all agricultural land). Complete conversion of all climatically suitable land to no-till management would sequester 3.3 Gt of carbon. This represents a 10% increase in carbon in the agricultural soils of the FSU. This estimated accumulation of carbon is associated with a new soil carbon equilibrium condition. Accumulation of carbon in the soil produced by a conversion from conventional to no-till management is expected to take at least 10 years. The carbon accumulation produced by conversion to no-till management is not a continuing process; once a new no-till equilibrium condition has been reached, additional quantities of atmospheric carbon will not be sequestered in agricultural soils through continued no-till management.

Helmer, E. H., and Sandra Brown. 2000. Gradient analysis of biomass in Costa Rica and an estimate of total emissions of greenhouse gases from biomass burning in Ecology of Tropical Development: The Myth of Sustainable Development in Costa Rica C. A. Hall, editor. Pp. 503-526. Academic Press.

One important component of sustainable development for a nation is the degree to which it can balance its greenhouse gas (GHG) exchange with the atmosphere. Clearing and burning of tropical forests for conversion to pasture and agriculture, most associated with economic expansion in many tropical countries, release GHGs such as CO₂, CH₄, N₂O, CO, and NO_x. Scientists at NHEERL-WED recently estimated the release of such GHGs from the conversion of a range of forest types in Costa Rica between 1940-1983. They also evaluated the influence of environmental gradients that affect the rates and patterns of deforestation and the carbon pools of the forest cleared on GHG emissions. Biomass estimates were derived from a series of previously

sampled plots of tree diameters and densities. From these estimates, national inventories of biomass were derived using estimates of the areal extent of forest cover, by life zone, for 1940 and 1983. The change in biomass associated with forest removal between the two dates was used to estimate transfer to the atmosphere of GHGs, using emission factors based on biomass burned, from previously published information. The estimated annual release of carbon-containing compounds over the 43-year period was 8.9 Tg CO₂-C, 1.2 Tg CO-C and 0.14 Tg CH₄-C. The estimated annual N₂O-N release was 1.28 x 10⁻³ Tg. Based on the relative warming potentials of CH₄ and N₂O, emissions of these gases during biomass burning have contributed about 30 percent of the warming potential of the CO₂ released in Costa Rica. The spatial pattern of GHG emissions reflected the historical pattern of forest clearing in which lowland and dry or mesic forests were developed before wet or high elevation forests. Sixty percent of trace gas emissions from deforestation and burning of the total fuel biomass between 1940 and 1983 was from burning of lowland moist and wet forests. The burning of lowland dry and moist forests contributed respectively 0.5%, 31% of emissions. However, these forests comprised only 0.6% and 15% of forest area in 1940 due to earlier deforestation that had started in those regions. In contrast, higher elevation wet forests comprised 14% of forest area in 1940, but together contributed only 7% of emissions. Thus trace gas emissions from deforestation were not proportional to the area of a given forest type. It was concluded that if clearing of the dry and moist forest for nations throughout the world has or will shift to clearing of wetter forests, the average warming potential from tropical forest burning could increase.

Homann, P.S., P. Sollins, M. Fiorella, T. Thorson and J.S. Kern. 1998. Regional soil organic carbon storage estimates for Western Oregon by multiple approaches. Soil Sci. Soc. Am. J. 62:789-796.

Soil is an important factor in regional and global C budgets because it serves as a reservoir of large amounts of organic C. In our study, we compared six approaches of estimating soil organic C (kg C m⁻², not including the surface organic horizon, hereafter called *soil C*) and its spatial pattern in the mountainous, largely forested western Oregon region. The approaches were (i) USDA NRCS pedons, (ii) other pedons, (iii) the State Soil Geographic Data Base (STATSGO), (iv) the United Nations Soil Map of the World, (v) the National Soil Geographic Data Base (NATSGO), and (vi) an ecosystem-complex map. Agreement between approaches varied with scale. For the entire region (10⁵ km²), estimates of average soil C varied from 4.3 to 6.8 kg C m⁻² for the 0- to 20-cm depth and from 12.1 to 16.9 kg C m⁻² for the 0- to 100-cm depth. At the subregional scale (= 10⁴ km²), all approaches indicated higher soil C in the coastal area than in the inland southern area, but relative amounts in other subregions varied among the approaches. At the subsubregional scale (= 10³ km²), soil C was consistent between individual STATSGO map units and NRCS pedons within those map units, but there was less agreement with other pedons. Rigorous testing of soil-C maps requires data from pedons that are located by objective criteria, in contrast to the subjectively located pedons now available. The uncertainty associated with regional soil-C amounts

and spatial patterns should be considered when soil-C maps are integrated into regional or global assessments of physical and biotic processes because simulation-model outputs may be sensitive to soil C.

Houghton, R.A., J.D. Unruh and P.A. Lefebvre. 1993. Current land cover in the tropics and its potential for sequestering carbon. *Global Biogeochemical Cycles* 7:305-320.

Emissions of carbon dioxide and other greenhouse gases from human activity are increasing the concentrations of these gases in the atmosphere. The Earth is expected to warm as a result, with consequences that are potentially highly disruptive to human societies. Reductions in the use of fossil fuels and in rates of deforestation worldwide will reduce emissions of CO₂, but atmospheric concentrations will continue to increase unless emissions are reduced by more than 60% (about 4.5 billion tons of carbon annually). Reforestation seems to offer one of the few means for reducing the atmospheric concentration of CO₂ over periods as short as human generations. We report here an approach for evaluating the potential for reforestation to help stabilize or even reduce the concentration of CO₂ in the atmosphere. Reforestation is defined broadly to include tree plantations, natural regrowth of secondary forests, and the practice of agroforestry. Our premise is that human use of the land has generally reduced woody biomass and that such lands have a potential for reaccumulating carbon if appropriately managed. We used published ground studies together with global vegetation index data from the NOAA 7 satellite to estimate current land cover in tropical regions. Then, superimposing this map of current land cover over maps depicting the distribution of vegetation cover prior to human disturbance, we obtained an estimate of about 3200 X 10⁶ ha in the tropics (almost 60% of the total land area considered) where woody biomass had been decreased, and where carbon might again be sequestered. We calculated the amount of carbon that could be withdrawn from the atmosphere and stored in woody biomass if several management options were implemented. Biomass accumulations were determined from forestry statistics. Application of the data on biomass to the areas suitable for accumulation of carbon yielded an estimate of potential accumulation of 160-170 Pg carbon, an amount equivalent to the accumulation of carbon in the atmosphere since the start of the industrial revolution, or to about 25 years of fossil fuel emissions at current rates. Estimates of both area and potential accumulation of carbon were crude, probably not better than ±50%. They are useful for suggesting the role that tropical lands might play in stabilizing atmospheric concentrations of CO₂, but they should not be used to suggest specific management options in individual countries. As maps with higher spatial resolution become available, however, the method should provide more precise estimates overall and in specific locations.

Kern, Jeffrey S. 1994. Spatial patterns of soil organic carbon in the contiguous United States. Soil Science Society of America Journal 58:439-455.

Spatial patterns and total amounts of soil organic C (SOC) are important data for studies of soil productivity, soil hydraulic properties, and the cycling of C-based greenhouse gases. This study evaluated several approaches for characterizing SOC to determine their relative merits. The first approach entailed grouping data from a global pedon SOC database by type of ecosystem, resulting in a total of 78.0 Pg of C (Pg = 10^{15} g) to 1-m depth for the contiguous USA. In a second approach, a pedon database was aggregated using soil taxonomy, resulting in a total for the contiguous USA of 80.7 ± 18.6 Pg of C when the great group SOC was spatially distributed with Major Land Resource Areas (MLRAS) using the 1982 National Resource Inventory (NRI) and the Soil Interpretation Record databases. The third approach used pedon and spatial data from a global soil map grouped by sod unit that resulted in 84.5 Pg of C for the contiguous USA. Although the ecosystem and soil taxonomic approaches resulted in similar totals, the taxonomic approaches are recommended because they gave more results in areas of Histosols, shallow soils, and soils with high rock fragment content. The ecosystem approach did not give reliable spatial patterns and is only useful for very broad-scale work where precisely georeferenced data are not needed. Grouping data by great group provided more information than grouping by order or suborder. The approach based on soil taxonomy is very useful because it is based on the NRI statistical framework and it allows stratification by other NRI items, such as land use and vegetation.

Kern, Jeffrey S., David P. Turner and Russty Dodson. 1997. Spatial patterns of soil organic carbon pool size in the northwestern United States. In Soil Processes and the Carbon Cycle edited by Rattan Lai, J.M. Kimble, Ronald F. Follett and Bobby A. Stewart, CRC Press. Pp. 29-43.

Researchers at the Western Ecology Division of the National Health and Environmental Effects Laboratory in Corvallis, Oregon have developed a map-based database of soil organic carbon for the Pacific Northwest with more detail than previously possible. Soil organic carbon is a measure of the amount of soil organic matter that plays a large role in providing plant nutrients, water, and a good physical environment for root growth. Soil organic matter is vulnerable to loss from, and can cause feedbacks to, environmental change. This dataset is based on information from a large number of sites that was generalized using computerized soil maps. The Pacific Northwest region is unique with areas of very large amounts of soil organic carbon that occur mainly along the Pacific coast, the Coast Range, and the Cascade Mountains. This work is the first result of a nearly completed effort to compile a national geographic

dataset of soil organic carbon, soil nitrogen, and soil water properties at spatial scales appropriate for studying environmental change.

Kolchugina, Tatyana P. and Ted S. Vinson. 1993. Climate warming and the carbon cycle in the permafrost zone of the former Soviet Union. *Permafrost and Periglacial Processes* 4:149-163.

The continuous permafrost zone of the former Soviet Union (FSU) occupies 5% of the land surface area of the earth and stores a significant amount of carbon. Climate warming could disrupt the balance between carbon (C) accumulation and decomposition processes within the permafrost zone. Increased temperatures may accelerate the rate of organic matter decomposition. At the same time, the productivity of vegetation may increase in response to warming. To assess the future carbon cycle within the permafrost zone under a climate warming scenario, it is necessary to quantify present carbon pools and fluxes. The present carbon cycle was assessed on the basis of an ecosystem/ecoregion approach. Under the present climate, the phytomass carbon pool was estimated at 17.0 Gt (10^9 t). The mortmass (coarse woody debris) carbon pool was estimated at 16.1 Gt. The soil carbon pool, including peatlands, was 139.4 Gt. The present rate of carbon turnover was 1.6 Gt/yr. Under a warming climate 0.46-0.72 Gt C/yr may be gradually released to the atmosphere, mainly due to the increase in mortmass and litter decomposition. The increased efflux may be concurrently balanced by carbon uptake by vegetation as a result of enhanced productivity and forest migration to the north. However, the possibility exists that a lag between increased carbon efflux and uptake by vegetation may occur. The equilibrium of the carbon cycle may be reestablished, but at a higher rate of carbon turnover. Climate warming may not influence the depth of the active layer in peatlands. The depth of the active layer in mineral soils was comparable with the depth of the organic layer. Consequently, degradation of permafrost may not have a substantial influence on future carbon emissions.

Kolchugina, Tatyana P. and Ted S. Vinson. 1993. Carbon balance of the continuous permafrost zone of Russia. *Climate Research* 3:13-21.

An increase in the atmospheric concentration of CO₂ is projected to cause climate warming. Warming of the permafrost environment could change the balance between carbon accumulation and decomposition processes and substantially disrupt the equilibrium of the carbon cycle. Warming may accelerate the rate of decomposition, which is limited by low temperatures, and thaw deeper layers of formerly frozen organic soils, making them available for decomposition. At the same time, productivity of vegetation may increase in response to warming. The continuous permafrost zone occupies approximately 40 % of Russian territory, and 5 % of the land surface area of the world. Disruption of the carbon cycle within the permafrost zone in Russia could have a profound effect on the global terrestrial carbon cycle. To evaluate changes in

the carbon cycle within the permafrost environment of Russia, it is necessary to quantify the present carbon pools and fluxes. Once the carbon balance is established under the present climate, potential disruptions under a warming climate can be identified. A framework to assess the carbon balance for the continuous permafrost zone of Russia was created. Under the present climate, the phytomass (live vegetation, above- and below-ground) carbon pool was 17.0 Gt (10^9 t). The mortmass (coarse woody debris) carbon pool was 16.1 Gt. The litter carbon pool was 6.4 Gt C and the soil carbon pool including peatlands was 139.4 Gt. Live vegetation and plant detritus (mortmass and litter) taken together were approximately one-third of the soil carbon pool. The rate of carbon turnover was 1.58 Gt yr^{-1} and the rate of humus formation was $0.083 \text{ Gt C yr}^{-1}$. The phytomass carbon pool of the permafrost zone was 19 % of the former Soviet Union (FSU) phytomass pool and 3 % of the world biomass carbon pool. The permafrost zone accumulated a significant amount of above- and below-ground plant detritus (mortmass and litter). Climate warming may cause forest migration to the north and increase net carbon accumulation in shrubby tundra ecosystems and ecosystems on soils of low permeability, compensating for possible carbon losses from tussock tundra. Shrubby tundra formations and gleyic soils occupy approximately one-half of the area of the Russian tundra biome. The degradation of permafrost would not directly affect the rate of carbon emissions from mineral soils and peatlands. The present depth of the active layer (i.e. layer of seasonal freezing and thawing) in mineral soils exceeds the depth of the organic horizons. In peatlands, thawing of the active layer could cause an additional mass of organic matter to become available for decomposition. However, thawing of the active layer in peatlands may not be this extensive because of the low thermal conductivity and high latent heat capacity of peat.

Kolchugina, Tatyana P. and Ted S. Vinson. 1993. Equilibrium analysis of carbon pools and fluxes of forest biomes in the former Soviet Union. Canadian Journal of Forest Research 23:81-88.

Natural processes in ocean and terrestrial ecosystems together with human activities have caused a measurable increase in the atmospheric concentration of CO_2 . It is predicted that an increase in the concentration of CO_2 will cause the Earth's temperatures to rise and will accelerate rates of plant respiration and the decay of organic matter, disrupting the equilibrium of the terrestrial carbon cycle. Forests are an important component of the biosphere, and sequestration of carbon in boreal forests may represent one of the few realistic alternatives to ameliorate changes in atmospheric chemistry. The former Soviet Union has the greatest expanse of boreal forests in the world; however, the role of Soviet forests in the terrestrial carbon cycle is not fully understood because the carbon budget of the Soviet forest sector has not been established. In recognition of the need to determine the role of Soviet forests in the global carbon cycle, the carbon budget of forest biomes in the former Soviet Union was assessed based on an equilibrium analysis of carbon cycle pools and fluxes. Net primary productivity was used to identify the rate of carbon turnover in the forest

biomes. Net primary productivity was estimated at 4360 Mt of carbon, the vegetation carbon pool was estimated at 110 255 Mt, the litter carbon pool was estimated at 17 525 Mt, and the soil carbon pool was estimated at 319 100 Mt. Net primary productivity of Soviet forest biomes exceeded industrial CO₂ emissions in the former Soviet Union by a factor of four and represented approximately 7% of the global terrestrial carbon turnover. Carbon stores in the phytomass and soils of forest biomes of the former Soviet Union represented 16% of the carbon concentrated in the biomass and soils of the world's terrestrial ecosystems. All carbon pools of Soviet forest biomes represented approximately one-seventh of the world's terrestrial carbon pool.

Kolchugina, Tatyana P. and Ted S. Vinson. 1993. Comparison of two methods to assess the carbon budget of forest biomes in the former Soviet Union. *Water, Air, and Soil Pollution* 70:207-221.

The sink of CO₂ and the C budget of forest biomes of the Former Soviet Union (FSU) were assessed with two distinct methods: (1) ecosystem/ecoregional, and (2) forest statistical data. The ecosystem/ecoregional method was based on the integration of ecoregions (defined with a GIS analysis of several maps) with soil/vegetation C data bases. The forest statistical approach was based on data on growing stock, annual increment of timber, and FSU yield tables.

Applying the ecosystem/ecoregional method, the area of forest biomes in the FSU was estimated at 1426.1 Mha (10⁶ ha); forest ecosystems comprised 799.9 Mha, non-forest ecosystems and arable land comprised 506.1 and 119.9 MHA, respectively. The FSU forested area was 28% of the global area of closed forests. Forest phytomass (i.e., live plant mass), mortmass (i.e., coarse woody debris), total forest plant mass, and net increment in vegetation (NIV) were estimated at 57.9 t C ha⁻¹, 15.5 t C ha⁻¹, 73.4 t C ha⁻¹, and 1.0 t C ha⁻¹ yr⁻¹, respectively. The 799.9 Mha area of forest ecosystems calculated in the ecosystem/ecoregional method was close to the 814.2 Mha reported in the FSU forest statistical data. Based on forest statistical data forest phytomass was estimated at 62.7 t C ha⁻¹, mortmass at 37.6 t C ha⁻¹; thus the total forest plant mass C pool was 100.3 t C ha⁻¹. The NIV was estimated at 1.1 t C ha⁻¹ yr⁻¹. These estimates compared well with the estimates for phytomass, total forest plant mass, and NIV obtained from the ecosystem/ecoregional method. Mortmass estimated from the forest statistical data method exceeded the estimate based on the ecosystem/ecoregional method by a factor of 2.4. The ecosystem/ecoregional method allowed the estimation of litter, soil organic matter, NPP (net primary productivity), foliage formation, total and stable soil organic matter accumulation, and peat accumulation (13.9 t C ha⁻¹, 125.0 t C ha⁻¹, 3.1 t C ha⁻¹ yr⁻¹, 1.4 t C ha⁻¹ yr⁻¹, 0.11, and 0.056 t C ha⁻¹ yr⁻¹, respectively). Based on an average value of NEP (net ecosystem productivity) from the two methods, and following a consideration of anthropogenic influences, FSU forests were estimated to be a net sink of approximately 0.5 Gt C yr⁻¹ of atmospheric C.

Kolchugina, Tatyana P. and Ted S. Vinson. 1993. Carbon sources and sinks in forest biomes of the former Soviet Union. *Global Biogeochemical Cycles* 7:291-304.

The carbon budget of the forest biomes of the former Soviet Union (FSU) and their sequestration potential were assessed by considering (1) net ecosystem productivity (NEP) of different age forest stands and actual forest coverage, (2) carbon flux related to forest fires, (3) the rate of peat accumulation, and (4) anthropogenic influences. The area of forest biomes in the FSU was estimated at 1426.1 million hectares (Mha); forest ecosystems comprised 7999 Mha, non-forest ecosystems and arable land comprised 506.3 and 119.9 Mha, respectively. The vegetation pool (phytomass and coarse woody debris) was 68.7 Gt C (carbon). The litter and soil carbon pools were 12.2 and 319.1 Gt C, respectively. The net primary productivity (NPP) of forest biomes ecosystems was 5.6 Gt C/yr, the rate of foliage formation was 2.3 Gt C/yr, the rate of humus formation was 161 Mt C/yr with 73 Mt C/yr in the stable form. The NEP' of the forest biomes was assessed from the data on NEP of young, middle-age, and premature forest stands. The NEP of the forest biomes was 825 Mt C/yr. Peat was accumulating at an average rate of 23 Mt C/yr. Carbon effluxes from mortmass, litter, and soil organic matter decomposition were calculated from the NPP, NEP, foliage, and humus formation rates. The efflux from mortmass decomposition was 2.6 Gt C/yr, from litter decomposition 2.1 Gt C/yr, and from soil organic matter decomposition 61 Mt C/yr. Peat combustion represented a carbon efflux of 30 Mt C/yr. The carbon efflux from forest fires and agricultural activities was 199 and 10 Mt C/yr, respectively. Carbon efflux from wood harvesting (carbon sequestration in regrowing vegetation was excluded) was 152 Mt C/yr. Considering all components of the natural carbon cycle and the anthropogenic influences, FSU forest biomes were, a net sink of 485 Mt C/yr of atmospheric carbon. The Siberian and Far East forests represent approximately 82% of the net sink. The total carbon sink in FSU forests was equivalent to one half of the annual CO₂ fossil fuel emissions in the FSU or one half the carbon released from deforestation in subtropical regions.

Krankina, O.N. and R.K. Dixon. 1992. Forest management in Russia - Challenges and opportunities in the era of perestroika. *Journal of Forestry*, June: 29-34.

The recent collapse of the former USSR and establishment of the Commonwealth of Independent States have had a dramatic impact on social, economic, and political events (Brandt 1992). After decades of forest resource depletion and degradation, recent changes have created opportunities for new developments in Russian forest management and for international cooperation in the field of forestry. Moreover, growing recognition of the importance of boreal forests in global environmental issues (e.g., global carbon cycle, greenhouse gas emissions) have stimulated interest in Russian

forest management and associated wood-processing industries (Dixon and Turner 1991. Brandt 1992).

This article will review significant historical trends in Russian forest management and current management issues. It will also examine the present and future impact of a changing society on the administration and management of forest systems, including opportunities for international cooperation.

Lee, Jeffrey J. and Rusty Dodson. 1996. Potential carbon sequestration by afforestation of pasture in the South-Central United States. *Agronomy Journal* 88:381-384.

Climate models indicate that increasing atmospheric concentrations of CO₂ and other greenhouse gases could alter climate globally. The Climate Change Action Plan commits the USA to reducing net greenhouse gas emissions by 106 x 10⁶ Mg C yr⁻¹ by the year 2000. One suggestion for reducing net emissions is to convert marginal grass pastures to pine (*Pinus* spp.) plantations in the South-Central USA. We used the Erosion/Productivity Impact Calculator (EPIC) model to estimate the amount of atmospheric C that could be sequestered by this suggested change in land use. Carbon flow dynamics at each of 100 randomly selected sites were simulated for 50 yr under two assumptions: (i) continuous pasture for 50 yr or (ii) pine plantations harvested every 25 yr. Carbon sequestered by conversion to pine plantations was calculated as the net change in off-site storage (i.e., in long-lived products and landfills), plus the change in soil organic C, plus (for the first harvest period) stand establishment. Average C-sequestration ((SE) was 40 (2 and 18 (2 Mg C ha⁻¹ for the first and second 25-yr harvest periods, respectively. In contrast, sequestration would have been 8.3 (0.6 Mg C ha⁻¹ as soil organic C if the sites had been left in continuous pasture for 50 yr, or 3 Mg C ha⁻¹ after correcting for release of C during manufacture of N-fertilizer. Extrapolated to the region, conversion of 3.6 x 10⁶ ha of marginal grass pasture to pine plantations could sequester 5.6 x 10⁶ C yr⁻¹ for the first 25 yr and 1.1 X 10⁶ Mg for the second 25 yr. If all types of marginal agricultural land in the region (4.6 x 10⁶ ha) were converted to forestry, the corresponding sequestration rates would be 7A x 10⁶ and 1.4 x 10⁶ Mg C yr⁻¹. In contrast, maintaining the land in continuous pasture would sequester 0.3 X 10⁶ Mg C yr⁻¹.

Lewis, David K., David P. Turner and Jack K. Winjum. 1996. An inventory-based procedure to estimate economic costs of forest management on a regional scale to conserve and sequester atmospheric carbon. *Ecological Economics* 16:35-49.

Estimation of the costs of managing forests to conserve and sequester atmospheric carbon is necessary to define the role of forests to mitigate the onset of projected global climate change. The role of forests as both carbon pools and an element in the flux of atmospheric carbon dictate new requirements in estimating the

costs of forest management to mitigate climate change. These requirements include recognition of the inventory as a capital stock in the estimation of the costs; the need to allow the integration of biological, social and economic considerations across nations and regions; and the need to facilitate consideration of the distributional impacts of forest policy alternatives. An inventory-based procedure is presented to estimate forest management costs based on recognition of the opportunity costs of holding forest inventories. To demonstrate this procedure, the costs of four policy scenarios projected in the carbon budget of the United States are examined. Based on the demonstration, the inventory-based procedure is shown to meet the requirements for estimating forest management costs to conserve and sequester atmospheric carbon on a regional scale. The demonstration also illustrates the potential of the procedure to provide insights into differences in costs associated with management of forest ecosystems among geographic regions and forest policies.

Lugo, Ariel E., Sandra Brown, Rusty Dodson, Tom S. Smith, and Hank H. Shugart. 1999. The Holdridge Life Zones of the conterminous United States in relation to ecosystem management. *Journal of Biogeography* 26:1025-1038

A fundamental first step in designing ecosystem management is the delineation and classification of ecologically homogeneous units. Scientists at WED in collaboration with colleagues in the Forest Service and University of Virginia developed a map of the life zones of the conterminous United States, based on the Holdridge Life Zone system, as a tool to aid in ecosystem management. The US is ecologically diverse with 38 life zones (34 % of the world's life zones and 85 % of the temperate ones) including one boreal, 12 cool temperate, 20 warm temperate (64 % of the country), four subtropical, and one tropical. Seventy four percent of the US falls in the "basal belt", 18 % is montane, 8 % is sub-alpine, 1% is alpine, and <0.1% is nival. The US ranges from superarid to superhumid, and the humid province is the largest (45% of the US). The most extensive life zone is the warm temperate moist forest, which covers 23% of the country. We compared the Holdridge life zone map with four other ecosystem classification maps (a global biome model, Bailey's ecoregions, Küchler potential vegetation, and land cover), all aggregated to four cover classes. Despite differences in the goals and methods for all these classification systems, there was a very good to excellent agreement among them for forests but poor for grasslands, shrublands, and non-vegetated lands. We considered the life zone approach to have many strengths for ecosystem mapping because it is based on climatic driving factors of ecosystem parameters and recognizes ecophysiological responses of plants; it is hierarchical and allows for the use of other mapping criteria at the association and successional levels of analysis; it can be expanded or contracted without losing functional continuity among levels of ecological complexity; it is a relatively simple system based on few empirical data; and it uses objective mapping criteria.

Phillips, D. L., S. L. Brown, P. E. Schroeder, and R. A. Birdsey. 2000. Toward error analysis of large-scale forest carbon budgets. *Global Ecology and Biogeography* 9:305-313.

The Framework Convention on Climate Change calls for national inventories of net greenhouse gas emissions, including carbon sources and sinks associated with forests and land cover change. Several such forest carbon budgets have been constructed, but little effort has been made to analyze the sources of error and how these errors propagate to determine the overall uncertainty of projected carbon fluxes. NHEERL/WED scientists, in collaboration with the USDA Forest Service, have completed an error analysis of estimates of changes in tree wood volume, the major component in determining whether US forests are acting as a carbon source or sink. The analysis was done for the southeastern U.S. and was based on data from the Forest Service's Forest Inventory and Analysis (FIA) program. Three major sources of error were recognized and quantified: (1) sampling error for sample plots; (2) measurement error for individual tree height and diameter; and (3) regression error for tree volume. The analysis determined how these error propagated to determine the uncertainty of the estimate of annual change in tree volume. The vast majority of the propagated error was due to sampling error. For the latest inventories for five southeastern states, current wood volume was estimated with a 95% confidence interval of approximately $\pm 1\%$, whereas annual change in wood volume was estimated with a 95% confidence interval of approximately $\pm 40\%$, due to the near balancing of tree growth and tree harvesting. Wood volume for southeastern US forests appears to be slightly increasing at this time, and would represent a small carbon sink. The methods developed and applied here should be useful to examine the sources of error and overall uncertainty in international efforts to quantify carbon fluxes associated with forests and land cover dynamics in various countries.

Riley, R.H., D.L. Phillips, M.J. Schuft and M.C. Garcia. 1997. Resolution and error in measuring land-cover change: effects on estimating net carbon release from Mexican terrestrial ecosystems. *Int. J. Remote Sensing* 18:121-137.

Reliable estimates of carbon exchange between terrestrial ecosystems and the atmosphere due to land-use change have become increasingly important. One source of land-use change estimates comes from comparing multi-date remote sensing imagery, though the effect of land-cover classification errors on carbon flux estimates has not been considered to our knowledge. We evaluated the integration of a land-cover change detection methodology using Landsat MultiSpectral Scanner (MSS) imagery with a regional carbon budget analysis. This work includes the incorporation of image classification accuracy information into the carbon budget of our sample landscape. Our analysis indicates that the Los Tuxtlas, Mexico study region

experienced an approximate net loss of $2-146 \times 10^6$ t C from 1986 to 1990. A carbon loss value which does not include classification error estimates is 34 per cent less than the adjusted value.

Schroeder, Paul. 1992. Carbon storage potential of short rotation tropical tree plantations. *Forest Ecology and Management* 50:31-41.

Forests are a major sink for carbon and play an important role in the global carbon cycle. Not only do forests contain huge amounts of carbon, they exchange it very actively with the atmosphere. Expanding the world's forests, therefore, may present an opportunity to increase the terrestrial carbon sink, and slow the increase in atmospheric CO₂ concentration. The tropical zones of the world seem particularly attractive for forestation because of the high rates of productivity that can potentially be attained there, and because there appear to be large areas of land that would benefit from tree planting. The analysis described here examines the carbon storage potential of short rotation tropical tree plantations in particular. Mean long-term carbon storage over multiple rotations was calculated for several commonly grown species. Rotation length, and hence the potential to accumulate biomass, is shown to be a key factor in the ability of plantations to remove carbon from the atmosphere over the long-term.

Schroeder, Paul. 1992. The potential of forestry and agroforestry practices to store carbon in the tropics. *World Resource Review* 4:23-41.

Terrestrial vegetation plays a pivotal role in the global carbon cycle. Not only are tremendous amounts of carbon stored in terrestrial vegetation, but large amounts are also actively exchanged between vegetation and the atmosphere. This suggests that vegetation, and specifically forests, can be used to store more carbon and thereby slow or partially offset the observed increase in atmospheric carbon dioxide. The tropical zones of the world seem particularly attractive for forestation because of the high rates of productivity that can potentially be attained there, and because there appear to be large areas of land that would benefit from tree planting. This analysis examined the carbon storage potential of short rotation tropical tree plantations in particular. Mean long-term carbon storage over multiple rotations was calculated for several commonly grown species. Mean long-term carbon storage ranged from 8-17 t C/ha in arid regions, to as high as 78 t C/ha in humid regions. Rotation length, and hence the potential to accumulate biomass, is shown to be a key factor in the ability of plantations to remove carbon from the atmosphere over the long-term. For comparison, the carbon storage potentials of some examples of agroforestry practices were also estimated.

Schroeder, Paul. 1993. Agroforestry systems: integrated land use to store and conserve carbon. *Climate Research* 3:53-60.

Agroforestry is a promising land use practice to maintain or increase agricultural productivity while preserving or improving fertility. From the perspective of climate change and the global carbon cycle, agroforestry practices are attractive for 2 reasons: they directly store carbon in tree components, and they potentially slow deforestation by reducing the need to clear forest land for agriculture. An extensive literature survey was conducted to evaluate the carbon dynamics of agroforestry practices and to assess their potential to store carbon. Data on tree growth and wood production were converted to estimates of carbon storage. Surveyed literature showed that median carbon storage by agroforestry practices was 9 t C ha⁻¹ in semi-arid, 21 t C ha⁻¹ in sub-humid, 50 t C ha⁻¹ in humid, and 63 t C ha⁻¹ in temperate ecoregions. The limited survey information available tended to substantiate the concept that implementing agroforestry practices can help reduce deforestation.

Schroeder, P. 1994. Carbon storage benefits of agroforestry systems. *Agroforestry Systems* 27:89-97.

The process of land degradation is a local phenomenon that occurs field by field. Because of the extent at which it is occurring, however, it also has a global dimension. Agroforestry represents a link between the local and global scales. From the farmer's perspective, agroforestry can be a way to increase crop yields and the diversity of products grown. An additional benefit is the creation of a carbon sink that removes carbon dioxide from the atmosphere. Successful agroforestry systems will also reduce land clearing and maintain carbon in existing vegetation. An extensive literature survey was conducted to evaluate the carbon dynamics of agroforestry practices and to assess their potential to store carbon. Data on tree growth and wood production were converted to estimates of carbon storage. Surveyed literature showed that median carbon storage by agroforestry practices was 9 tC/ha in semi-arid, 21 tC/ha in sub-humid, 50 tC/ha in humid, and 63 tC/ha in temperate ecozones. The limited survey information available substantiated the concept that implementing agroforestry practices can help reduce deforestation.

Schroeder, P. 1995. Organic matter cycling by tropical agroforestry systems: a review. *Journal of Tropical Forest Science* 7:462-474.

The trend in shifting tropical agriculture to shorter fallow periods and ultimately to attempts at continuous cultivation usually leads to land degradation and reduced productivity. This often results in the clearing of more forest land. Although the effects of these practices are most apparent at local scales, large releases of carbon dioxide and other greenhouse gases from forest clearing and land use change also have implications for the global environment. Agroforestry appears to be a promising technique to achieve sustainable land use by conserving soil organic matter. This paper compares the organic matter dynamics of agroforestry systems to successful long fallow agricultural systems. For the studies surveyed, agroforestry systems on average

returned $7.4 \text{ t ha}^{-1} \text{ y}^{-1}$ (± 0.8) of organic matter to the soil surface in the form of prunings. This is within the range of litter production observed for long fallow systems. There is also evidence that the sustainability of agroforestry systems may be constrained by soil properties. On infertile soils, a limited potential for increasing nutrient inputs results in reduced plant growth, litterfall, and nutrient cycling. Implementation of agroforestry systems as an alternative to continuous cropping, however, should slow the loss of soil organic carbon and extend the cropping period.

Schroeder, Paul. 1996. A carbon budget for Brazil: influence of future land-use change. *Climatic Change* 33: 369-383.

Because of its large area of high C density forests and high deforestation rate, Brazil may play an important role in the global C cycle. The study reported here developed an estimate of Brazil's biotic $\text{CO}_2\text{-C}$ budget for the period 1990-2010. The analysis used a spreadsheet C accounting model based on three major components: a conceptual model of ecosystem C cycling, a recently completed vegetation classification developed from remote-sensing data, and published estimates of C density for each of the vegetation classes. The dynamics of the model came from estimates of disturbance to ecosystems that release C and estimates of recovery from past disturbance that store C. The model was projected into the future with three alternative estimates of the rate of future land use change. Under all three deforestation scenarios Brazil was a C source in the range of about $3\text{-}5 \times 10^9 \text{ MgC}$ over the 20-yr study period.

Schroeder, Paul, Sandra Brown, Jiangming Mo, Richard Birdsey and Chris Cieszewski. 1997. Biomass estimation for temperate broadleaf forests of the United States using inventory data. *Forest Science* 43:424-434.

A potentially valuable data source for estimating forest biomass is forest volume inventory data that are widely collected and available throughout the world. In this paper we present a general methodology for using such data to reliably estimate aboveground biomass density (AGBD) and to develop expansion factors for converting volume directly to AGBD from USDA Forest Service Forest Inventory and Analysis (FIA) data. Growing stock volume inventory data and stand tables were combined with independently developed biomass regression equations to estimate AGBD and to calculate biomass expansion factors (BEF: factors that convert volume to mass, accounting for noncommercial components) for the extensive oak-hickory and maple-beech-birch forest types of the eastern United States. Estimated aboveground biomass for both forest types ranged between 28 and 200 Mg ha^{-1} . Expansion factors decreased from more than 4.0 at low growing stock volume to nearly 1.0 when growing stock volume was as high as $190 \text{ m}^3 \text{ ha}^{-1}$, consistent with theoretical expectations. In stands with low AGBD ($< 50 \text{ Mg ha}^{-1}$), small diameter trees ($< 10 \text{ cm}$ diameter) contained up to 75% of the AGBD in trees $\geq 10 \text{ cm}$ diameter; this proportion dropped to $< 10\%$ for

stands with AGBD > 175 Mg ha⁻¹. The similarity of our results for two major forest types suggests that they may be generally applicable for estimating AGBD from inventory data for other temperate broadleaf forests. Further, the pattern between BEF and stand volume was similar to that obtained for tropical broadleaf forests, except that tropical forests generally had larger BEFs than temperate forests at a given volume. The implications of these results suggest that a recent assessment of forest biomass in developed countries is too low.

Schroeder, P.E., R.K. Dixon and J.K. Winjum. 1993. Forest management and agroforestry to sequester and conserve atmospheric carbon dioxide. *Unasylva* 173:52-60.

The accumulation of greenhouse gases in the atmosphere, particularly carbon dioxide (CO₂), is projected to alter the earth's climate. The potential role of forests in carbon sequestration has recently been evaluated by a number of authors (Marland, 1988; Andraisko, Heaton and Winnett, 1991; Grainger, 1991; Houghton, Unruh and Lefebvre, 1991; Sedjo and Solomon, 1991). Although they are preliminary, these analyses suggest that forest conservation, establishment and management as well as agroforestry could contribute to global carbon sequestration and conservation while providing goods and services in local communities of many countries. At the same time, the authors of these analyses agree on one critical point: forest carbon sequestration options alone will not solve the problems related to greenhouse gases. Addressing the climate change issue on a global scale will require complex adaptation and mitigating measures affecting all social and economic sectors. Moreover, it is clear that any forestry-based responses should represent a sound policy that is independent of the predicted global warming, and should produce net benefits in addition to those that may ultimately arise in the climate change context.

Schroeder, Paul E. and Jack K. Winjum. 1995. Assessing Brazil's carbon budget: I. Biotic carbon pools. *Forest Ecology and Management* 75:77-86

Brazil contains the world's largest expanse of tropical forest, but its forests are experiencing high levels of conversion to other uses. There is concern that releases of CO₂ and other greenhouse gases resulting from deforestation will contribute to global climate change. The total amount of C that could be released by deforestation depends upon the amount currently contained in the terrestrial biota and soils. Knowledge of the areas of Brazil's major ecosystems and land use types and their C densities was used to estimate the total amount of C stored in vegetation, litter and coarse woody debris, and soils. The total estimated C pools were (58-81) x 10⁹ Mg C in vegetation, (6-9) x 10⁹ Mg C in litter and coarse woody debris, and about 72 x 10⁹ Mg C in soil. Over 80% of the vegetation pool was contained in the closed tropical moist forests of Brazil.

Schroeder, Paul E. and Jack K. Winjum. 1995. Assessing Brazil's carbon budget: II. Biotic fluxes and net carbon balance. *Forest Ecology and Management* 75:87-99.

The global carbon cycle is affected by the annual addition of 7.0×10^9 Mg CO₂-C to the atmosphere from deforestation and burning of fossil fuels. Because of its large area of high C density forests and high deforestation rate, Brazil may play an important role in the global C cycle. The study reported here developed an annual C budget for Brazil for the year 1990. The budget was based on a simple conceptual model of ecosystem C storage and flux, a newly developed vegetation map based on remote sensing data, and published information on carbon densities and flux parameters. The analysis presents an estimate of net anthropogenic flux from land use change and includes an estimate of C accumulation in secondary forests. Net CO₂-C emission estimates ranged from 174×10^6 to 233×10^6 Mg C year⁻¹. Timber harvest in plantations and burning fossil fuels contributed additional emissions of about 107×10^6 Mg C year⁻¹. Brazil's combined net C emissions represented 4-5% of the global total.

Schroeder, Paul and Jack K. Winjum. 1995. Brazil's carbon budget for 1990. *Interciencia* 20:68-75.

The recent history of deforestation in the Amazon region of Brazil is well known (Malingreau and Tucker 1988, Fearnside 1990, INPE 1992, Skole and Tucker 1993). A major reason for alarm over the rate and magnitude of deforestation in Brazil has been concern that the reduction in vegetation releases carbon dioxide (CO₂) and other greenhouse gases that may contribute to global climate change (Crutzen and Andreae 1990, Houghton 1991, Fearnside 1991, Subak et al. 1993). While deforestation releases CO₂, however, tree growth elsewhere accumulates atmospheric carbon (C). Discussions of CO₂ releases from tropical deforestation have tended to focus on gross releases and have generally not considered the effects of carbon uptake. The objective of this paper is to examine the net C balance for Brazil by estimating both CO₂-C release and uptake.

Schufft, Michael J., Jerry R. Barker and Michael A. Cairns. 1998. Spatial Distribution of Carbon Stocks in Southeast Mexican Forests. *Geocarto International* 13:77-86.

Carbon (C) stocks for southeast Mexican forests for the years 1990-1991 were calculated by two different methods. The first method multiplied land area of each forest by C densities of phytomass, necromass, and soil-organic matter. A digital map derived from Advanced Very High Resolution Radiometer (AVHRR) imagery provided forest areas. Carbon-density values were obtained from ecological studies reported in

the literature. The second method calculated C densities from climate-based regression models for each forested pixel in the AVHRR cover map. A combination of the two methods was used to calculate C stocks because neither approach was suitable for all forests. Land area was estimated as 13 Mha for the tropical evergreen forest, 7 Mha for the tropical deciduous forest, and 7 Mha for the oak-coniferous forest. Carbon stocks for tropical evergreen, tropical deciduous, and oak coniferous forests were 3.12, 1.30, and 0.92 PgC, respectively. The southeast forests contribute approximately 40% to total C stocks in all Mexican forests.

Solomon, Allen M. 1996. Potential responses of global forest growing stocks to changing climate, land use and wood consumption. *Commonwealth Forestry Review* 75:65-75.

The assessment addresses future impacts on forest growing stocks generated by changing climate and land use, and by increasing harvests, both a function of a growing human population. It uses IPCC scenarios (IS92a) to define future regional population changes in order to estimate future wood consumption; output from coupled atmosphere-ocean general circulation models (ECHAM, GFDL, UKTR) to define future regional climate changes; and static global vegetation models (BIOME, IMAGE) which include land cover, to quantify forest biomass responses to changing climate and land use. The simulations indicate that climate driven vegetation impacts would be greatest in boreal regions, reducing biomass there by 16-30% and global biomass from 5-16%. Land-use driven vegetation impacts would be greatest in the tropics, reducing biomass there by 30%, and global biomass by 8%. Although scenarios of wood consumption indicate increases by 2 to 3 times during the same period, consumption does not exceed average annual wood increments in temperate and boreal forests. However, consumption exceeds current annual increments in tropical forests by about 2% by the year 2050. Uncertainties derived from processes not modeled suggest consumption eventually may be greater than projected in tropical and boreal forests, and supply may be less than projected in boreal forests.

Solomon, Allen M. and Andrew P. Kirilenko. 1997. Climate change and terrestrial biomass: what if trees do not migrate? *Global Ecology and Biogeography Letters* 6:139-148.

Climate changes induced by doubling atmospheric greenhouse gas (2XGHG) concentrations are expected to affect the distribution of global vegetation and thereby, the amount of carbon it stores. The role of the terrestrial biosphere as a source or sink for carbon during climate change is critical: if increased GHG concentration and warming enhances carbon storage, thereby reducing atmospheric concentrations, the climate changes would also be ameliorated. If instead, carbon storage is reduced, the warming could induce a positive feedback to further increase atmospheric

concentrations already on the rise from burning of fossil fuels. Differing climate-defined static vegetation classifications have been used to project biome distributions for climates induced by 2XGHGs. These projections assume that species extirpation and invasion will track perfectly distributions of climate variables and they predict enhanced terrestrial carbon storage. However, theoretical calculations and palaeoecological evidence suggest an alternative, more realistic simplifying assumption: trees will be extirpated but will not invade new territory before 2XGHG climate is attained. We projected global terrestrial carbon under future climates using both assumptions. Simulated terrestrial carbon under delayed immigration decreased 7 to 34 Pg from modern values in contrast to increases projected under instant migration in this and earlier model exercises.

Solomon, Allen M. and Rik Leemans. 1997. Boreal forest carbon stocks and wood supply: past, present and future responses to changing climate, agriculture and species availability. *Agricultural and Forest Meteorology* 84:137-151.

The paper assesses the role in boreal forest growth played by environment. It examines past changes in climate coupled with glaciation, and future changes in climate coupled with agricultural land use and tree species availability. The objective was to define and evaluate potential future changes in wood supply and global carbon stocks. Calculations were based on a standard static vegetation model (BIOME 1.1) driven by the most recent climate change scenarios from three coupled ocean-atmosphere general circulation models (GCMs). The results indicated that boreal terrestrial carbon stocks increased greatly following the retreat of continental ice sheets, before which boreal forests covered only about a third the amount of land they cover now. Carbon stocks and wood supplies in boreal forests were also projected to increase if vegetation stabilized under all three future climate scenarios (6-15%). However, the opposite response occurred with the addition of expected constraints on forest growth, provided by the tags in immigration of tree species suitable for warmed climate. This transient depauperate condition reduced wood supplies considerably (4-6%). Inclusion of present and future agricultural land uses permitted by a warming climate forced carbon stocks and wood supplies to decline even more (10-20%). The decline in boreal carbon stocks is the equivalent of 1-2.6 Pg year⁻¹ emitted to the atmosphere (rather than the 1-2 Pg year⁻¹ global modelers hypothesize is currently being taken up by vegetation from the atmosphere), during the time greenhouse gases are expected to double in concentration.

Solomon, Allen M., I. Colin Prentice, Rik Leemans and Wolfgang P. Cramer. 1993. The interaction of climate and land use in future terrestrial carbon storage and release. *Water, Air, and Soil Pollution* 70:595-614.

The processes controlling total carbon (C) storage and release from the terrestrial biosphere are still poorly quantified. We conclude from analysis of paleodata and climate-biome model output that terrestrial C exchanges since the last glacial maximum (LGM) were dominated by slow processes of C sequestration in soils, possibly modified by C starvation and reduced water use efficiency of trees during the LGM. Human intrusion into the C cycle was immeasurably small. These processes produced an averaged C sink in the terrestrial biosphere on the order of 0.05 Pg yr^{-1} during the past 10,000 years.

In contrast, future C cycling will be dominated by human activities, not only from increasing C release with burning of fossil fuels, and but also from indirect effects which increase C storage in the terrestrial biosphere (CO_2 fertilization; management of C by technology and afforestation; synchronous early forest succession from widespread cropland abandonment) and decrease C storage in the biosphere (synchronous forest dieback from climatic stress; warming-induced oxidation of soil C; slowed forest succession; unfinished tree life cycles; delayed immigration of trees; increasing agricultural land use). Comparison of the positive and negative C flux processes involved suggests that if the C sequestration processes are important, they likely will be so during the next few decades, gradually being counteracted by the C release processes.

Based only on tabulating known or predicted C flux effects of these processes, we could not determine if the earth will act as a significant C source from dominance by natural C cycle processes, or as a C sink made possible only by excellent earth stewardship in the next 50 to 100 yrs. Our subsequent analysis concentrated on recent estimates of C release from forest replacement by increased agriculture. Those results suggest that future agriculture may produce an additional 0.6 to 1.2 Pg yr^{-1} loss during the 50 to 100 years to CO_2 doubling if the current ratio of farmed to potentially-farmed land is maintained; or a greater loss, up to a maximum of 1.4 to 2.8 Pg yr^{-1} if all potential agricultural land is farmed.

Turner, David P., Joseph V. Baglio, Andrew G. Wones, Derek Pross, Richard Vong, Bruce D. McVeety and Donald L. Phillips. 1991. Climate change and isoprene emissions from vegetation. *Chemosphere* 23:37-56.

A global model was developed for estimating spatial and temporal patterns in the emission of isoprene from vegetation under the current climate. Results were then used to evaluate potential emissions under doubled- CO_2 climate scenarios. Current emissions were estimated on the basis of vegetation type, foliar biomass (derived from the satellite-generated Global Vegetation Index), and global databases for air temperature and photoperiod. The model had a monthly time step and the spatial resolution was 0.5 degrees latitude and longitude. Emissions under patterns of precipitation and temperature projected for a doubling of atmospheric CO_2 were

estimated based on predicted changes in the areal extent of different vegetation types, each having a specific rate of annual isoprene emissions. The global total for current emissions was 285 Tg. The calculated isoprene emissions under a doubled-CO₂ climate were about 25 % higher than current emissions due mainly to the expansion of tropical humid forests which had the highest annual emission rates. An increase in isoprene emissions would be likely to increase atmospheric concentrations of ozone and methane, which are important greenhouse gases, and thus act as a positive feedback to global warming. Detailed treatment of this question, however, will require incorporation of these emission surfaces into global atmospheric chemistry models.

Turner, David P., Greg J. Koerper, Mark E. Harmon and Jeffrey J. Lee. 1995. A carbon budget for forests of the conterminous United States. *Ecological Applications* 5:421-436.

The potential need for national-level comparisons of greenhouse gas emissions, and the desirability of understanding terrestrial sources and sinks of carbon, has prompted interest in quantifying national forest carbon budgets. In this study, we link a forest inventory database, a set of stand-level carbon budgets, and information on harvest levels in order to estimate the current pools and flux of carbon in forests of the conterminous United States. The forest inventory specifies the region, forest type, age class, productivity class, management intensity, and ownership of all timberland. The stand-level carbon budgets are based on growth and yield tables, in combination with additional information on carbon in soils, the forest floor, woody debris, and the understory. Total carbon in forests of the conterminous U.S. is estimated at 36.7 Pg, with half of that in the soil compartment. Tree carbon represents 33% of the total, followed by woody debris (10%), the forest floor (6%), and the understory (1%). The carbon uptake associated with net annual growth is 331 Tg, however, much of that is balanced by harvest-related mortality (266 Tg) and decomposition of woody debris. The forest land base at the national level is accumulating 79 Tg/yr, with the largest carbon gain in the Northeast region. The similarity in the magnitude of the biologically driven flux and the harvest-related flux indicates the importance of employing an age-class-based inventory, and of including effects associated with forest harvest and harvest residue, when modeling national carbon budgets in the temperate zone.

Turner, David P. and Rik Leemans. 1992. Equilibrium analysis of projected climate change effects on the global soil organic matter pool. *In Carbon Cycling in Boreal Forests and Subarctic Ecosystems Workshop Proceedings*. Corvallis, OR: US EPA.

Increased rates of soil organic matter decomposition may represent a significant positive feedback to global warming. As a step towards assessing the potential magnitude of this response, an equilibrium analysis was performed in which

representative carbon pools were associated with each vegetation type, and the Holdridge vegetation/climate correlation system was used to compare distributions of the vegetation types under the current climate and doubled-CO₂ climate scenarios from four general circulation models. Two of the general circulation models predicted a net loss of below-ground carbon (55-101 Pg) because of large decreases in the areal extent of tundra and boreal ecosystems with high levels of belowground carbon storage. Vegetation redistribution projected under the other two general circulation models would result in the accumulation of carbon (5-41 Pg) in the biosphere; however, this accumulation was driven primarily by an increase in the areal extent of tropical rain forests that is unlikely given constraints imposed by anthropogenic factors. Additional considerations not treated by the equilibrium approach support the likelihood of a transient pulse of carbon from the soil to the atmosphere.

Turner, David P., Jack K. Winjum, Tatyana P. Kolchugina and Michael Cairns. 1997. Accounting for biological and anthropogenic factors in national land-base carbon budgets. *Ambio* 26:220-226.

Efforts to quantify net greenhouse gas emissions at the national scale, as required by the United Nations Framework Convention on Climate Change, must include both industrial emissions and the net flux associated with the land base. In this study, data on current land use, rates of land-cover change, forest harvest levels, and wildfire extent were analyzed under a common framework for three countries in order to compare net CO₂-carbon flux, and to identify key research areas. In the Former Soviet Union (FSU) and the conterminous United States (US), the stand age-class distribution on the forested land and the rate of logging tended to be the most important factors in the land-base flux, whereas in Brazil the rate of land-cover change and the vegetation regrowth in secondary forests on abandoned agricultural or grazing land were critical. The areas of greatest uncertainty for the FSU and US analyses related to the rates of woody debris and soil organic matter accumulation and to limitations in the age-class based inventory data available. In Brazil, the initial biomass in forests subject to deforestation, and the area of recovering secondary forest, were identified as important research issues. Continued database development, and close attention to methodologies for quantifying carbon flux, will be necessary if carbon budget assessments are to be of use to the policy community.

Turner, David P., Jack K. Winjum, Tatyana P. Kolchugina, Ted S. Vinson, Paul E. Schroeder, Donald L. Phillips, and Michael A. Cairns. 1998. Estimating the Terrestrial C Pools of the Former Soviet Union, Conterminous U.S., and Brazil. *Climate Research* 9:183-96.

Scientists find terrestrial C pools of the former Soviet Union, conterminous U.S., and Brazil contain 38% OF Laboratory/Western Ecology Division have completed analyses of the terrestrial carbon (C) pools of the former Soviet Union (SUf),

conterminous United States (USc), and Brazil. The estimated C pools are among the first completed for these national areas. Improved global estimates of C pools are a continuing need because of the dominant role C plays in the dynamics of atmospheric greenhouse gases and, therefore, global warming projections. Results showed that the estimated total C in the vegetation, litter layer, and soil for the three nation areas was 839 petagrams (PgC) or 925 billion English tons of C in 1990. This pool was 38% of the world's estimated terrestrial C pool contained in an area, which combined, occupies 28% of the world's lands (excluding Antarctica). For the SUf, the total C pool estimated was 601 PgC (663 tons C). Peatland and forest areas contained the largest C pools accounting for 37% and 23% of the total. The estimated C pool for the USc was 86 PgC (95 tons C). Forest area represented the largest C pool with 43% of the total. For Brazil, the estimated C pool was 153 PgC (167 tons C). The largest C pool, forest, contained 71% of Brazil's total estimated terrestrial carbon.

Vinson, Ted S. and Tatyana P. Kolchugina. 1993. Pools and fluxes of biogenic carbon in the former Soviet Union. *Water, Air, and Soil Pollution* 70:223-237.

The Former Soviet Union (FSU) was the largest country in the world. It occupied one-sixth of the land surface of the Earth. An understanding of the pools and fluxes of biogenic C in the FSU is essential to the development of international strategies aimed at mitigation of the negative impacts of global climate change. The territory of the FSU is represented by a variety of climate conditions. The major part of the FSU territory is in the boreal and temperate climatic zones. The climate in the FSU changes from arctic and subarctic in the North to subtropical and desert in the South. From west to east, the climate makes a transition from maritime to continental to monsoon. The vegetation of the FSU includes the following principal types: forest, woodland, shrubland, grassland, tundra, desert, peatlands and cultivated land. Arctic deserts and tundra formations are found in the northern part of the FSU, deserts and semi-deserts are found in the southern part.

A framework was created to assess pools and fluxes of biogenic C in the FSU. Under the framework spatially distributed data were analyzed with a geographic information system to isolate ecoregions. The soil-vegetation complexes for the ecoregions were linked to FSU data bases of soil and vegetation C pools and fluxes. The C budget for an ecoregion was established by multiplying the area of the ecoregion by the unit area C content(s) or rate(s) associated with the soil-vegetation complex for the ecoregion. The C pools and fluxes for all the ecoregions were summed to arrive at an initial estimate of the pools and fluxes of biogenic C for 95% of the territory of the FSU. Based on the framework, net primary productivity (NPP) for the FSU was estimated at $6.17 \pm 1.65 \text{ Gt C yr}^{-1}$, the vegetation C pool (live plant mass and coarse woody debris) at $118.1 + 28.5 \text{ Gt C}$, the litter C pool at $18.9 \pm 4.4 \text{ Gt C}$, and total soil C pool at $404.0 \pm$

38.0 Gt C. The phytomass pool of the FSU was 16% of the global biomass pool. The soil and litter pools of the FSU were 20 and 23% of the global soil and detritus pools, respectively. The NPP of the FSU was 10% of the global NPP. The phytomass, soil and litter densities of the FSU were greater than the world average. The productivity of terrestrial ecosystems in the FSU was slightly lower than the world average.

Watrud, L.S., S. Maggard, T. Shiroyama, C.G. Coleman, M.G. Johnson, K.K. Donegan, G. Di Giovanni, L.A. Porteous, E.H. Lee. 2003. Bracken (*Pteridium aquilinum* L.) Frond biomass and rhizosphere microbial community characteristics are correlated to edaphic factors. *Plant and Soil* 249: 359-371.

Bracken fern is a broadly distributed species which has been proposed as an indicator in models of global climate change. Frond, rhizosphere and bulk soil samples were obtained from bracken fern growing in three sites located along an elevational and mean annual temperature gradient in the Oregon Cascade Mountains. Soil at the low elevation site had significantly higher soil N and significantly lower soil Fe content. Soil pH was similar at the low and high elevation sites (pH 6.2 and pH 6.1, respectively), and lower at the mid elevation site (pH 5.5). Principal component analysis scores of metabolic profiles of rhizosphere, but not bulk soil, microbial communities obtained on Biolog plates differed significantly between lower and higher elevation sites. Using inocula adjusted to a uniform percent transmittance, the shortest incubation times until targeted average well color development values were reached was observed with samples from the low elevation site. Frond biomass values were highest at the low elevation site. Mycorrhizal infection of bracken was slightly, but significantly lower at the low elevation site. Relative proportions of microfungus saprophyte populations found in bracken rhizosphere samples differed significantly between the 3 sites. A conceptual model is presented which shows potential links between edaphic and other environmental factors with bracken biomass and the metabolic profiles and community structure of rhizosphere microbial populations.

Winjum, Jack K., Sandra Brown, and Bernhard Schlamadinger. 1998. Forest harvests and wood products: sources and sinks of atmospheric carbon dioxide. *Forest Science* 44;272-84.

Scientists at the Corvallis National Health and Environmental Research Laboratory/Western Ecology Division have completed analyses of the carbon (C) emissions as carbon dioxide to the atmosphere resulting from forest harvests and wood products usage. The estimated C emissions are among the first completed for this human activity on a world level. Improved global estimates of C emissions are a continuing need because of the dominant role C plays in the dynamics of atmospheric greenhouse gases and, therefore, global warming projections. Results showed that an

estimated 967 million metric tons of CO₂-C were emitted in 1990 as a result of forest harvests and wood products usage. Of the total, 59% came from developing countries and 41% came from developed countries. Country level estimates in millions of tons were: for developing nations, Brazil, 73; Colombia, 6; India, 81; Indonesia, 55; and Ivory Coast, 4; and for the developed nations, Canada, 46; Finland, 14; Japan, 12; New Zealand, 3; and U.S. 131. Among the variables that most consistently and strongly affected such C emissions for 1990 were: roundwood production, post-harvest slash left to oxidize, and commodity wood put into uses > 5 yrs.

Winjum, Jack K., Robert K. Dixon and Paul E. Schroeder. 1992. Estimating the global potential of forest and agroforest management practices to sequester carbon. *Water, Air, and Soil Pollution* 64:213-227.

Forests play a prominent role in the global C cycle. Occupying one-third of the earth's land area, forest vegetation and soils contain about 60% of the total terrestrial C. Forest biomass productivity can be enhanced by management practices, which suggests that, by this means, forests could store more C globally and thereby slow the increase in atmospheric CO₂. The question is how much C can be sequestered by forest and agroforest management practices. To address the question, a global database of information was compiled to assess quantitatively the potential of forestry practices to sequester C. The database presently has information for 94 forested nations that represent the boreal, temperate and tropical latitudes. Results indicate that the most promising management practices are reforestation in the temperate and tropical latitudes, afforestation in the temperate regions, and agroforestry and natural reforestation in the tropics. Across all practices, the median of the mean C storage values for the boreal latitudes is 16 tCha⁻¹ (n=46) while in the temperate and tropical latitudes the median values are 71 tCha⁻¹ (n=401) and 66 tCha⁻¹ (n=170), respectively. Preliminary projections are that if these practices were implemented on 0.6 to 1.2 x 10⁹ ha of available land over a 50-yr period, approximately 50 to 100 GtC could be sequestered.

Winjum, Jack K., Robert K. Dixon and Paul E. Schroeder. 1993. Forest management and carbon storage: an analysis of 12 key forest nations. *Water, Air, and Soil Pollution* 70:239-257.

Forests of the world sequester and conserve more C than all other terrestrial ecosystems and account for 90% of the annual C flux between the atmosphere and the Earth's land surface. Preliminary estimates indicate that forest and agroforest management practices throughout the world can enhance the capability of forests to sequester C and reduce accumulation of greenhouse gases in the atmosphere. Yet of the 3600 x 10⁶ ha of forests in the world today, only about 10% (350 x 10⁶ ha) are actively managed. The impetus to expand lands managed for forestry or agroforestry purposes lies primarily with nations having forest resources. In late 1990, an assessment was initiated to evaluate the biological potential and initial site costs of managed forest and agroforest systems to sequester C. Within the assessment, 12 key forested nations were the focus of a special analysis: Argentina, Australia, Brazil, Canada, China, Germany, India, Malaysia, Mexico, South Africa, former USSR, and USA. These nations contain 59% of the world's natural forests and are representative of the world's boreal, temperate, and tropical forest biomes. Assessment results indicate that though the world's forests are contained in 138 nations, a subset of key nations, such as the 12 selected for this analysis, can significantly contribute to the global capability to sequester C through managed tree crops. Collectively, the 12 nations are estimated to have the potential to store 25.7 PgC, once expanded levels of practices such as reforestation, afforestation, natural regeneration and agroforestry are implemented and maintained. Initial site costs based upon establishment costs for management practices are less than US\$33/Mg C.

Winjum, Jack K. and David K. Lewis. 1993. Forest management and the economics of carbon storage: the nonfinancial component. *Climate Research* 3:111-119.

Globally, forests fix and store significant amounts of carbon. This attribute aids in reducing the buildup of atmospheric CO₂. Forest management can increase biomass productivity on lands suitable for forest growth thereby enhancing the uptake of CO₂ by terrestrial ecosystems. Worldwide, however, only about 10% of the 3.6 billion ha of forests are currently under management, suggesting a considerable potential for expansion. Before national and international policy makers commit to increasing the level of forest management, they need information on the benefits and costs of forest management for this objective. Financial evaluations of forest management benefits and costs are not uncommon. But nonfinancial considerations are often not considered in such analyses, and they can change resulting conclusions. Using a series of 30 plantation regimes from around the world, this paper demonstrates the influence of including the nonfinancial cost (i.e. opportunity cost) of forest growing stock in selecting the most favorable opportunities for investments in carbon storage through forest management.

Winjum, Jack K., Richard A. Meganck and Robert K. Dixon. 1993. Expanding global forest management: an (easy first(proposal. *Journal of Forestry* 91:38-42.

As world leaders become increasingly aware of the contributions of sustainable forest resources to political, social, economic, and environmental health, interest is growing for a world treaty or protocol on forest management and protection (Laarman and Sedjo 1992). One culmination of this interest was the adoption of principles for sustainable development and management of world forests at the Earth Summit in June 1992 (Hill et al. 1992) and a call for subsequent meetings to discuss target dates, program sizes, and global organization (World Resources Institute 1992a).

Although the forest principles underscored many key topics related to global forests, this paper focuses on one of those themes--expanding global forest management--and offers suggestions, goals, and an (easy first(approach to facilitate what might at first appear to be a formidable undertaking.

Winjum, Jack K. and Paul E. Schroeder. 1997. Forest plantations of the world: their extent, ecological attributes, and carbon storage. *Agricultural and Forest Meteorology* 84:153-167.

Forest plantations in the world total approximately 103×10^6 ha, and annual rates of establishment are about 10.5×10^6 ha. A total of 124 countries throughout the high, middle, and low latitudes of the world establish new plantations each year. In addition to supplying an array of goods and services, plantations contribute to carbon (C) storage. This analysis integrates information across latitudes to evaluate the potential of forest plantations to achieve these goals. For example, mean carbon storage (MCS) in above- and below-ground phytomass of artificially established plantations generally increases from high to low latitudes ranging from 47 to 81 t C ha⁻¹. Over a 50-year period, harvests from these plantations are credited with storing C at 10, 34, 15, and 37 t C ha⁻¹ in wood products in the high, middle, low-dry, and low-moist latitudes, respectively. Using today's distribution of plantations among the four zones of latitude and C storage values from this analysis, the world's plantations can be credited with storing an area-weighted average of 91 t C ha⁻¹ including MCS and durable-wood products. Based upon these estimates, the world total C storage in forest plantations today is approximately 11.8 Pg C with an annual increase of 0.178 Pg C year⁻¹.