Annotated Bibliography – Western Ecology Division
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CARBON CYCLE

Bachelet, Dominique. 1993. Climate change impacts on net primary production in China. International Symposium of Climate Change, Natural Disasters, and Agricultural Strategies.

Several studies have estimated the potential effects of greenhouse gas-induced climate change on various systems using outputs of general circulation models (GCMs). The purpose of this study was to generate comparable estimates of potential impacts on net primary production using the GCM climate scenarios in a very simple net primary production model. We also wanted to identify the most likely limiting factor that would follow a change in global climate.

Bachelet, Dominique, Jeffrey Kern and Michael Tölg. 1995. Balancing the rice carbon budget in China using spatially-distributed data. Ecological Modelling 79:167-177.

Rice paddies are a source of food for over half of the world population and also the source of a very potent greenhouse gas, methane. We used the FAO soil map of the world to produce a high-resolution rice location map. Using published GIS-linked climate-based and yield-based empirical models, we calculated the net primary production (NPP) of rice fields in China. Values varied between $136 \cdot 10^{12}$ g C using climate drivers from digital maps to $222 \cdot 10^{12}$ g C using published grain production figures for 1988. We assumed that either 5% of NPP or 30% of the organic matter added to the soil during rice cultivation was transformed into methane, adding up to a total emission of 7 to $16 \cdot 10^{12}$ g C. We also gathered published data on fertilizer inputs and management practices and, using linear regression techniques, calculated the correlation between methane emission and carbon inputs to obtain a total emission value of $10 \cdot 10^{12}$ g C. Using the results for NPP ($135\text{-}222 \cdot 10^{12}$ g C). methane emission ($7\text{-}16 \cdot 10^{12}$ g C) and published grain production figures, we balanced the carbon budget of rice paddies estimating soil respiration at $51 \cdot 10^{12}$ g C for all Chinese rice fields or 159 g C m^{-2} y^{-1} for an average Chinese rice field, a number which agrees with published values for similar systems. This result confirmed our assumption that rice soils in China, where rice cultivation has occurred for several thousand years, were neither losing nor accruing carbon. However, any changes in the hydrology of these soils may transform them into significant carbon sources. Using the Food and Agricultural Organization (FAO) digital map of the soils of the world, we estimated soil carbon content for the rice-growing regions of China and quantified the potential carbon losses that would occur if these soils were drained.

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.

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 thcir existing large areal extcnt, 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 currcnt fossil fuel C emissions) (Table 11.1). Tropical forcsts 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, 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^{--r} 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 photosysnthesis 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 forst 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, biodiversiry, and wood and noriwood 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 wich 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 cultrivation. Together wich irs 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., 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 Ramirez-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 estimat 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.

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 CO_2 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.

Gucinski, Hermann, David P. Turner, Charles Peterson and Greg Koerper. 1993. Carbon pools and flux on forested lands of the United States. "Workshop on Carbon Cycling inBoreal Forests and Subarctic Ecosystem," editors: Ted Vinson and Tatanya Kolchugina. Corvallis, OR, USEPA.

The potential for global climate change due to the anthropogenic release of carbon dioxide, methane, and other gases has focused attention on global forests. Forest ecosystems are a central component of the global carbon cycle and are of interest and concern for three reasons. One is the current contribution of deforestation, panicularly in tropical latitudes, to the build-up of greenhouse gases (Houghton 1991). The second is the potential climate induced redistribution of the world's forests, which may result in the release of potentially large quantities of carbon (Prentice and Fung 1990, Dixon and Turner 1991). This may be a transient release due to changes in disturbance regimes over broad spatial scales (Overpeck et al. 1990, Neilson and King 1992), or a long term change in terrestrial carbon storage if forests are replaced by biomes having relatively low above- and belowground carbon concentrations (Smith et al. in press). Lastly, there is the possibility that forests could be managed to increase the sequestering of carbon (Dixon et al. 1991) and thereby both delay the onset of climate change or diminish its magnitude (Trexier 1991). Such management could take advantage of possible benefits that may accrue from the direct effects of higher ambient CO_2 levels (Strain and Cure 1985, Bazzaz and Garbuff 1988), or from the potential expansion of tropical forests due to the increased water availability predicted by some general circulation models (Neilson 1990).

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 CO_2, CH_4, N_2O, CO, and NOx. 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 CO_2-C, 1.2 Tg CO-C and 0.14 Tg CH_4-C . The estimated annual N_2O-N release was 1.28 x 10-3 Tg. Based on the relative warming potentials of CH_4 and N_2O, emissions of these gases during biomass burning have contributed about 30 percent of the warming potential of the CO_2 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.

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 CO_2, 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 CO_2 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 CO_2 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 10^6 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 CO_2, 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.

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/vr mav 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 CO_2 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 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 CO_2 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 CO_2 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 (10^6 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 3 7.6 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 fitter, sod 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 CO_2 fossil fuel emissions in the FSU or one half the carbon released from deforestation in subtropical regions.

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 ±1%, whereas annual change in wood volume was estimated with a 95% confidence interval of approximately ±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 x 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. 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 CO_2-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 3-5 x 10^9 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 m^3 ha^{-1}, consistent with theoretical expectations. In stands with low AGBD (< 50 Mg ha^{-1}), small diameter trees (< 10 cm diameter) contained up to 75% of the AGBD in trees $\geq$ 10 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, 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 CO_2 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 10^9 Mg C in vegetation, (6-9) x 10^9 Mg C in litter and coarse woody debris, and about 72 x 10^9 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 x 10^9 Mg CO_2-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 CO_2-C emission estimates ranged from 174 X 10^6 to 233 x 10^6 Mg C year^{-1}. Timber harvest in plantations and burning fossil fuels contributed additional emissions of about 107 x 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 (CO_2) 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 CO_2, however, tree growth elsewhere accumulates atmospheric carbon (C). Discussions of CO_2 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 CO_2-C release and uptake.

Schuft, Michael J., Jerry R. Barker and Michaael 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 ears 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-CO_2 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-CO_2 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 CO_2-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 ± 1.65 Gt C yr^{-1}, the vegetation C pool (live plant mass and coarse woody debris) at 118.1 + 28.5 Gt C, the litter C pool at 18.9 ± 4.4 Gt C, and total soil C pool at 404.0 ±
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.

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.

CARBON SEQUESTRATION IN FORESTS

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 fo 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 (3.6×10^7 a) of grassland and 1.5 Mha (3.7×10^6 a) of forestland. CRP1 scenario simulated the likely outcome of the CRP as contracts expire in 1996 with the return of 8.7 Mha (2.1×10^6 a)of grassland and 0.4 Mha (9.9×10^5 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 (9.9×10^6 a) of new cropland. The WRP began in 1996 with 2 Mha (4.9×10^6 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 X 10^6 ha cropland converted to 14.7 X 10^6 ha grassland and of 1.5 X 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 X 10^6 ha grassland and of 0.4 X 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 X 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 CO_2 and carbon sequestration in forests. *Front Ecol Environ* 2(6): 315–322.

Rising CO_2 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 CO_2 released into the atmosphere by human activities. Many people believe that the amount of carbon that forests sequester will increase as CO_2 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 CO_2 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, 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 CO_2 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 CO_2 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 d 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 CO_2 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.

Cairns, M. A. and K. Lajtha. 2005. Effects of Succession on Nitrogen Export in the West-Central Cascades, Oregon. Ecosystems (2005) 8: 583–601.

This study examined impacts of succession on N export from 20 headwater stream systems in the west central Cascades of Oregon, a region of low anthropogenic N inputs. The seasonal and successional patterns of nitrate (NO3)N) concentrations drove differences in total dissolved N concentrations because ammonium (NH4)N) concentrations were very low (usually < 0.005 mg L)1) and mean dissolved organic nitrogen (DON) concentrations were less variable than nitrate concentrations. In contrast to studies suggesting that DON levels strongly dominate in pristine watersheds, DON accounted for 24, 52, and 51% of the overall mean TDN concentration of our young (defined as predominantly in stand initiation and stem exclusion phases), middle-aged (defined as mixes of mostly understory reinitiation and older phases) and oldgrowth watersheds, respectively. Although other studies of cutting in unpolluted forests have suggested a harvest effect lasting 5 years or less, our young successional watersheds that were all older than 10 years still lost significantly more N, primarily as NO3)N, than did watersheds containing more mature forests, even though all forest floor and mineral soil C:N ratios were well above levels reported in the literature for leaching of dissolved inorganic nitrogen. The influence of alder may contribute to these patterns, although hardwood cover was quite low in all watersheds; it is possible that in forested ecosystems with very low anthropogenic N inputs, even very low alder cover in riparian zones can cause elevated N exports. Only the youngest watersheds, with the highest nitrate losses, exhibited seasonal patterns of increased summer uptake by vegetation as well as flushing at the onset of fall freshets. Older watersheds with lower N losses did not exhibit seasonal patterns for any N species. The results, taken together, suggest a role for both vegetation and hydrology in N retention and loss, and add to our understanding of N cycling by successional forest ecosystems influenced by disturbance at various spatial and temporal scales in a region of relatively low anthropogenic N input.

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 CO_2 concentration that may lead to global warming. Forestation and other forest management options to sequester CO_2 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., CO_2-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 m^2 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 $Y = \exp\{-2.173 + 0.868 \ln(D^2 * TH) + 0.0939/2\}$, 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.

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 CO_2 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 CO_2. 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 (CO_2 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 10^6 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. Daivd 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 x 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 $\pm$ 0.4 petagrams of carbon per year, whereas forest area expansion and growth in mid- and high-latitude forest sequestered 0.7 $\pm$ 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 firest 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 x 106 to 10.0 x 106 ha. Approximately 15 000 - 25 000 forest fires occurred annually during this period. Mean annual direct CO_2-C emissions from wildfire was approximately 0.05 Pg over this 21 -year period. Total post-fire biogenic CO_2-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 x 106 to 631 x 106 ha of forest, will be affected. An additional 6.7 x 106 to 12.6 x 106 ha of Russian boreal forest are projected to bum annually if general circulation model based vegetation-change scenarios are achieved within the next 50 years. The direct flux of CO_2-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 CO_2 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 CO_2 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 agro-forestry 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 Modelling 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, biogeocheniical Sulphur and Nitrogen cycles), as well as on human factors such as demographics, economic growth, technology, and resource management policies.

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-afforestation 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.

Jaramillo, Víctor J., J. Boone Kauffman, Lyliana Rentería-Rodríguez, Dian L. Cummings, and Lisa J. Ellingson. Biomass, Carbon, and Nitrogen Pools in Mexican Tropical Dry Forest Landscapes. Ecosystems (2003) 6: 609–629.

Tropical dry forest is the most widely distributed land-cover type in the tropics. As the rate of land-use/land-cover change from forest to pasture or agriculture accelerates worldwide, it is becoming increasingly important to quantify the ecosystem biomass and carbon (C) and nitrogen (N) pools of both intact forests and converted sites. In the central coastal region of Mexico, we sampled total aboveground biomass (TAGB), and the N and C pools of two floodplain forests, three upland dry forests, and four pastures converted from dry forest. We also sampled belowground biomass and soil C and N pools in two sites of each land-cover type. The TAGB of floodplain forests was as high as 416 Mg ha^{-1}, whereas the TAGB of the dry forest ranged from 94 to 126 Mg ha^{-1}. The TAGB of pastures derived from dry forest ranged from 20 to 34 Mg ha^{-1}. Dead wood (standing and downed combined) comprised 27%–29% of the TABG of dry forest but only about 10% in floodplain forest. Root biomass averaged 32.0 Mg ha^{-1} in floodplain forest, 17.1 Mg ha^{-1} in dry forest, and 5.8 Mg ha^{-1} in pasture. Although total root biomass was similar between sites within land-cover types, root distribution varied by depth and by size class. The highest proportion of root biomass occurred in the top 20 cm of soil in all sites. Total aboveground and root C pools, respectively, were 12 and 2.2 Mg ha^{-1} in pasture and reached 180 and 12.9 Mg ha^{-1} in floodplain forest. Total aboveground and root pools, respectively, were 149 and 47 kg ha^{-1} in pasture and reached 2623 and 264 kg ha^{-1} in floodplain forest. Soil organic C pools were greater in pastures than in dry forest, but soil N pools were similar when calculated for the same soil depths. Total ecosystem C pools were 306 Mg ha^{-1} in floodplain forest, 141 Mg ha^{-1} in dry forest, and 124 Mg ha^{-1} in pasture. Soil C comprised 37%–90% of the total ecosystem C, whereas soil N comprised 85%–98% of the total. The N pools lack of a consistent decrease in soil pools caused by land-use change suggests that C and N losses result from the burning of aboveground biomass. We estimate that in Mexico, dry forest landscapes store approximately 2.3 Pg C, which is about equal to the C stored by the evergreen forests of that country (approximately 2.4 Pg C). Potential C emissions to the atmosphere from the burning of biomass in the dry tropical landscapes of Mexico may amount to 708 Tg C, as compared with 569 Tg C from evergreen forests.

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 chances 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. Ile 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.

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 agorforestry 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 svstems on average returned 7.4 t ha^{-1} y^{-1} ($\pm$ 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, 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 (CO_2), 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. 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, 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 CO_2 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 and 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.

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-l (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 cases 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 U S$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 co 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 x 10^6 ha, and annual rates of establishment are about 10.5 x 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 io 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 $year^{-1}$.

CARBON SEQUESTRATION IN SOILS

Börner, T., M.G. Johnson, P.T. Rygiewicz, 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 littler layer material. Calibrating the instrument for this specific condition should improve the overall estimate of the litter layer water content.

Compton, J.E., L.S. Watrud, L.A. Porteous, and S. DeGrood. 2004. Response of Soil Microbial Biomass and Community Composition to Chronic Nitrogen Additions at Harvard Forest. Forest Ecology and Management 196:143-158.

Soil microbial communities may respond to anthropogenic increases in ecosystem nitrogen (N) availability, and their response may ultimately feedback on ecosystem carbon and N dynamics. We examined the long-term effects of chronic N additions on soil microbes by measuring soil microbial biomass, composition and substrate utilization patterns in pine and hardwood forests at the Harvard Forest Chronic N Amendment Study. Functional and structural genes for important N cycling processes were studied using DNA community profiles. In the O horizon soil of both stand types, N additions decreased microbial biomass as determined by chloroform fumigation-extraction. Utilization of N-containing substrates was much lower in N-treated pine soils than in the controls, indicating that N additions reduced potential microbial activity in the pine stand. Counts of fungi and bacteria as determined by direct and culture techniques were quite variable and did not show a clear response to N additions. Nitrogen additions, however, strongly influenced microbial community DNA profiles. The ammonium oxidizing gene *amoA* generally was found in high N treated soils, but not in control soils. The *nifH* gene for N_2-fixation was more difficult to amplify in the pine N treated soil than the controls, suggesting that the potential for nitrogen fixation was depressed after chronic N additions. Our findings indicate that chronic N additions decreased microbial biomass and altered DNA community profiles. These changes in microbial community structure and function may be an important component of the response of terrestrial ecosystems to increased N supply due to human activities.

Cordoba, A.S., de Mondonca, M.M., Sturmer, S.L., Rygiewicz, P.T. 2001. Diversity of Arbuscular Mycorrhizal Fungi Along a Sand Dune Stabilization Gradient: A Case Study at Praia de Joaquina on the Ilha de Santa Catarina, South Brazil. Mycoscience 42: 379-387.

Species diversity of abuscular mycorrhizal fungi (AMF) was assessed along a dunes stabilization gradient (embyonic dune, foredune and fixed dune) at Praia da Joaquina (Joaquina Beach), Ilha de Santa Catarina. These dunes served as a case study to assess whether diversity and mycorrhizal inoculum potential increase along the gradient. Ten soil samples were collected from each stage, pooled, and then six, 100g soil sub-samples taken to identify and enumerate spores. Twelve AMF species were detected, and all three families in Glomales were represented. Gigasporaceae species dominated in the embryonic dune while Glomaceae species dominated in the fixed dune. Total spore numbers and richness increased as the dunes became more stabilized. However, indices of Margalef, Simpson and Shannon reached maximal values at different stages suggesting that species abundance distributions were different at each stage. In both embryonic and fixed dunes, species abundance data fit the broken stick model while in the foredune, the log series model best described the data. Mycorrhizal inoculum potential followed spore numbers and increased along the gradient suggesting that spores are important in initiating root colonization in this system. Relationships between edcaphic factors and functional roles of Glomales families as determinants of AMF distribution are discussed.

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 CO_2 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. CO_2, CH_4) for various ecosystems. An equilibrium analysis of changes in global below-ground carbon storage due to a doubled-CO_2 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.

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.

Hobbie E.A., M.G. Johnson, P.T. Rygiewicz, D.T. Tingey, D.M. Olszyk 2004. Isotopic estimates of new carbon inputs into litter and soils in a four-year climate change experiment with Douglas-fir. Plant and Soil 259: 331-343.

Soil carbon is a major reservoir of terrestrial carbon and a potential sink of atmospheric CO_2. Therefore, numerous studies have attempted to quantify soil carbon responses to environmental factors such as global warming, elevated CO_2, or ecosystem management.
Changes in soil carbon can be based on soil $^{13}C^{12}C$ ratios, however, there are problems in interpreting the results based on current methodology. We present a modified method to quantify the effects of global climate change on plant inputs of carbon to soil that accounts for isotopic fractionation between biotic inputs and new soil organic matter. In a four-year study, the effects of elevated CO_2 and temperature were determined for reconstructed Douglas-fir [*Pseudotsuga mensiezii* (Mirb.) Franco] ecosystems. The ^{13}C patterns in litter and mineral soil horizons were measured and compared to □^{13}C patterns in needles, fine roots, and coarse roots. The ^{13}C patterns clearly indicated the proportion of new carbon added to each soil layer which was 7-9% for the top litter layers, 13-15% for the top mineral soil (A) horizon, and 4% for the lower (B2 and C) soil horizons. However, under the nitrogen-limited growth conditions used in this study, neither elevated CO_2 nor temperature affected the soil carbon sequestration patterns. The isotopic enrichment of newly incorporated soil carbon relative to plant inputs was about 2‰. This enrichment must be accounted for when using shifts in soil □^{13}C to calculate inputs of plant carbon into the soil, and has probably resulted in significant underestimates of new soil carbon inputs in prior global change studies that assumed no isotopic fractionation between biotic inputs and newly incorporated soil carbon.

Hobbie, E.A., F.S. Sánchez, and P.T. Rygiewicz. 2004. Carbon use, nitrogen use, and isotopic fractionation of ectomycorrhizal and saprotrophic fungi in natural abundance and ^{13}C-labelled cultures. Mycol. Res 108(7): 725-736.

Natural abundances of 10 strains of ectomycorrhizal fungi and 7 strains of saprotrophic fungi were analyzed using natural abundances of N and C isotopes. Results quantified sources of N and C and isotopic fractionation among taxa.

Hobbie, E.A., Watrud, L.S., Maggard, S., Shiroyama, T., Rygiewicz, P.T. 2003. Carbohydrate Use by Litter and Soil Fungi Assessed Through Stable Isotopes and BIOLOG® Assays. Soil Biology & Biochemistry 35: 303-311.

Soil fungi are integral to decomposition in forests, yet identification of probable functional roles of different taxa is problematic. Here, we compared carbohydrate assimilation patterns derived from stable isotope analyses on cultures with those produced from cultures on Biolog® SP-F plates for 12 taxa of soil- and litter-inhabiting saprophytic fungi isolated from Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) ecosystems. To determine the relative assimilation of malt extract versus sucrose by ^{13}C stable isotope analyses, we cultured fungi with malt extract plus either C_3- or C_4-derived sucrose as carbon sources. *Rhodotorula graminis* and *Fusarium oxysporum* assimilated the highest proportion of sucrose, a *Mortierella* isolate and the unidentified sterile isolate FPC 341 assimilated the lowest proportion of sucrose, and the remainder of the cultures assimilated similar and intermediate proportions of sucrose. We then used Biolog SF-P plates to determine the metabolic activity of the fungi on eight carbohydrates similar to those present in the isotopic study: glucose, fructose, galactose, maltose, sucrose, cellobiose, lactose, and glycogen. In general, metabolic activity was greatest on maltose and glucose and lowest on fructose. Two of the isolates (*Aspergillus flavus* and *F. oxysporum*) had higher metabolic activity on the glucose-containing disaccharide cellobiose than on glucose, strongly suggesting preferential uptake of cellobiose compared to glucose and suggesting the potential ability to use cellulose. The high metabolic activity of these cultures on galactose, a primary constituent of hemicellulose, also suggested cellulolytic capabilities. With metabolic activity normalized among cultures, the *Mortierella* isolate and the unidentified sterile isolate FPC 341 had the lowest metabolic activity on sucrose, results generally consistent with assimilation patterns calculated isotopically. Low metabolic activities of *R. graminis* and *F. oxysporum* on maltose in Biolog assays were qualitatively consistent with isotopic results. The small assimilation of maltose in these two cultures when sucrose was also present suggested that sucrose inhibited maltose uptake. Assimilation of sucrose as calculated isotopically was correlated with the ratio of sucrose : maltose assimilation as calculated from Biolog assays (r^2=0.45, p=0.0145, n=12). These results indicate that stable isotope studies and Biolog methodologies may provide complementary information to characterize functional roles of fungi in forest litter and soil.

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 ecosvstem-complex map. Agreement between approaches varied with scale. For the entire region (10^5 km^2), 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 subregioual scale (= 10^4 km^2), 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 (= 10^3 km^2), 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 subjectivelv 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.

Johnson, Mark G., Elissa R. Levine and Jeffrey S. Kern. 1995. Soil organic matter: distribution, genesis, and management to reduce greenhouse gas emissions. Water, Air and Soil Pollution 82:593-615.

In this paper we describe the accumulation of soil organic matter (SOM) during pedogenesis and the processes that can lead to the emission of greenhouse gases (CO_2, CH_4, N_20) to the atmosphere via SOM decomposition and denitrification. We discuss the role of management on SOM accumulation and loss, and the potential for controlling emission or consumption of greenhouse gases by soils. We conclude that under current climate conditions there are global scale opportunities to reduce greenhouse gas emissions from soils and increase the indirect sequestration of greenhouse gases in soils through improved soil management.

Johnson, Mark G. 1995. The role of soil management in sequestering soil carbon. *In* International Symposium on Soil Processes and Management Systems: Greenhouse Gas Emissions and Carbon Sequestration. Advances in Soil Science.

Soils are an important component of the global carbon cycle and serve as a large reservoir of terrestrial carbon. The amount of carbon in any soil is a function of the soil forming factors including: climate, relief, organisms, parent material, and time. Over the centuries, humans, usually included as part of the "organisms" factor, have profoundly influenced the dynamics and sequestration of carbon in soils by their land use and management practices. These practices include cultivation, deforestation, and draining wet soils. In general, human activities have decreased the amount of carbon held in

affected soils. With the concern over increasing concentrations of greenhouse gases, humans need to consider how soil management affects greenhouse gas emissions from soil and the sequestration of carbon in soils, and to look for ways to protect and manage soil carbon. This paper examines soil management practices and their effects on greenhouse gas emissions and carbon sequestration. Included is an analysis of how management practices affect the physical and chemical environment of soil and how these in turn affect greenhouse gas emissions and the soil carbon sequestration potential.
support

Kern, J.S. and M.G. Johnson. 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Science Society of America Journal 57:200-210.

Soil organic matter is the largest global terrestrial C pool and is a source of CO_2, CH_4, and other greenhouse gases. Changes in soil organic C (SOC) content and fossil fuel C emissions in response to conversion of conventional tillage to conservation tillage in the contiguous USA for field crop production by the year 2020 were projected by developing a model based on published data, and geographic databases of current conservation tillage usage and agricultural SOC. Three scenarios of conservation tillage use, 27% (current usage), 57% (Scenario 2), and 76% (Scenario 3) of field cropland planted, were considered. The SOC content for major field crops to 30-cm depth was 5304 to 8654 Tg C (Tg = 10^{12} g), with 1710 to 2831 Tg C at 0- to 8-cm depth, and 1383 to 2240 Tg C at 8- to 15-cm depth. Maintaining current levels of conventional tillage until 2020 would result in 31 to 52 Tg SOC loss. Scenario 2 conventional tillage resulted in 18 to 30 Tg C SOC loss, and Scenario 3 yielded 9 to 16 Tg SOC loss, which were C savings of 21 to 36 Tg C over maintaining current levels of tillage. Conversion of conventional tillage to no-till resulted in 80 to 129 Tg C gain in soil for Scenario 2, and 286 to 468 Tg C for Scenario 3. No-till and conventional tillage had similar SOC contents below the 15-cm depth. Minimum tillage conserved current levels of SOC but did not consistently increase SOC above levels of conventional tillage. Fossil fuel emissions from field manipulations and herbicide production for conventional tillage are 53 kg C ha^{-1} yr^{-1}, minimum tillage is 45 kg C ha^{-1} yr^{-1}, and 29 kg C ha^{-1} yr^{-1} for no-till. Fuel emissions for maintaining current levels of tillage practices are 157 Tg C, 149 Tg C for Scenario 2, and 146 Tg C for Scenario 3 for 30 yr. Increasing the amount of conservation tillage to Scenario 3 levels will change these agricultural systems from sources of C (188-209 Tg C) to C sinks (131-306 Tg C). The SOC benefit of Scenario 3 (277-452 Tg C) is equivalent to 0.7 to 1.1% of the total projected U.S. fossil fuel C emissions for the next 30 yr.

Martin, Kendall J. and Paul T Rygiewicz. Fungal-specific PCR primers developed for analysis of the ITS region of environmental DNA extracts. 2005. BMC Microbiology 2005, 5:28.

Background: The Internal Transcribed Spacer (ITS) regions of fungal ribosomal DNA (rDNA) are highly variable sequences of great importance in distinguishing fungal species by PCR analysis. Previously published PCR primers available for amplifying these sequences from environmental samples provide varying degrees of success at discriminating against plant DNA while maintaining a broad range of compatibility. Typically, it has been necessary to use multiple primer sets to accommodate the range of fungi under study, potentially creating artificial distinctions for fungal sequences that amplify with more than one primer set. **Results:** Numerous sequences for PCR primers were tested to develop PCR assays with a wide range of fungal compatibility and high discrimination from plant DNA. A nested set of 4 primers was developed that reflected these criteria and performed well amplifying ITS regions of fungal rDNA. Primers in the 5.8S sequence were also developed that would permit separate amplifications of ITS1 and ITS2. A range of basidiomycete fruiting bodies and ascomycete cultures were analyzed with the nested set of primers and Restriction Fragment Length Polymorphism (RFLP) fingerprinting to demonstrate the specificity of the assay. Single ectomycorrhizal root tips were similarly analyzed. These primers have also been successfully applied to Quantitative PCR (QPCR), Length Heterogeneity PCR (LH-PCR) and Terminal Restriction Fragment Length Polymorphism (T-RFLP) analyses of fungi. A set of wide-range plant-specific primers were developed at positions corresponding to one pair of the fungal primers. These were used to verify that the host plant DNA was not being amplified with the fungal primers. **Conclusion:** These plant primers have been successfully applied to PCR-RFLP analyses of forest plant tissues from above- and below-ground samples and work well at distinguishing a selection of plants to the species level. The complete set of primers was developed with an emphasis on discrimination between plant and fungal sequences and should be particularly useful for studies of fungi where samples also contain high levels of background plant DNA, such as verifying ectomycorrhizal morphotypes or characterizing phylosphere communities.

Tingey, D.T., D.L. Phillips, and M.G. Johnson. 2003. Optimizing minirhizotron sample frequency for an evergreen and deciduous tree species. New Phytologist 157: 155-161.

Data on the production and turnover of fine roots are needed to parameterize plant growth models and to assess the impacts of stressors on ecosystems. Increasingly minirhizotrons are being used in natural ecosystems to determine fine root production and turnover, as they provide a nondestructive, *in situ* method for studying fine root dynamics. WED scientists recently completed a study to determine how image collection frequency influences estimates of fine root production and turnover for an evergreen (*Pseudotsuga menziesii* [Mirb.] Franco) and a deciduous (*Tilia cordata* Mill.) tree. Because it is costly to collect and analyze root images it is desirable to minimize the number of images collected. However, if the sampling interval is too long, fine roots can appear and disappear between samplings, leading to underestimates of production and turnover. For example, if a sampling interval of 8 weeks is used, 24 and 35% of the fine root production in *P. menziesii* and *T. cordata*, respectively, is not measured compared to the 0.5 week interval. Fine root turnover displays the same sensitivity to sample frequency as production. The conclusion that sampling frequency influences estimates of fine root production and turnover applies not only to the minirhizotron method but also to sequential coring and in-growth cores, methods that also rely on periodic sampling to estimate production and turnover. These findings will lead to improved estimates of fine root production and turnover and will assist in developing better models and risk assessment procedures to determine the impacts of stressors on vegetation. (Contact D.T. Tingey, 541-754-4621; tingey.dave@epa.gov)

Tingey, D.T., D.L. Phillips, M.G. Johnson, P.T. Rygiewicz, P.A. Beedlow, W.E. Hogsett. 2005. Estimates of Douglas-fir fine root production and mortality from minirhizotrons. Forest Ecology and Management 204:359-370.

Minirhizotrons were used to assess the influence of soil resources on fine root (diameter 2 mm) production, mortality, and standing crop over a 2-year period. Two study sites were located, along an elevational transect, in the Oregon Cascade Mountains in mature (>100 years old), closed-canopy Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) stands growing on soils with differing resource levels. The low resource site (LRS) had lower soil N (0.15% total N) and lower available water capacity (83 mm) than the high resource site (HRS), where soil N was 0.25% total N and available water capacity was 145 mm. Minirhizotron tubes were installed at each site during August 1994. To allow time for recovery from tube installation, the first root images were collected in late fall 1995 and then at 4 week intervals thereafter, except when snow prevented sample collection at the LRS. Root data from soil cores collected near the minirhizotron tubes were used to convert the minirhizotron data to the units of g m□2 (to a depth of 60 cm). Tree bole growth, at the HRS, was about twice that at the LRS, while fine root biomass, at the HRS, was only a third of that at the LRS. Seasonally, fine root production started before the onset of bole growth. Fine root standing crop, production, and mortality were consistently higher at the LRS than at the HRS. These findings support the concept that plants allocate more C to fine roots when soil resources are low. Our estimates of fine root production and mortality tend to be larger than previous reports for Douglas-fir stands. These differences can be attributed, in part, to the failure of the previous studies to account for fine root production and mortality between sampling events.

Tingey, D.T., M.G. Johnson, and D.L. Phillips. 2005. Independent and contrasting effects of elevated CO_2 and N-fertilization on root architecture in *Pinus ponderosa*. Trees 19: 43-50.

The effects of elevated CO_2 and N-fertilization on the architecture of Pinus ponderosa (Dougl. ex P. Laws & C. Laws) fine roots and their associated mycorrhizal symbionts were measured over a 4-year period using minirhizotron tubes. The study was conducted in open-top field-exposure chambers located near Placerville, Calif. A replicated (3 replicates), 3×3 factorial experimental design with three CO_2 concentrations [ambient air (354 μmol mol^{-1}), 525 μmol mol^{-1}, and 700 μmol mol^{-1}] and three rates of N-fertilization (0, 100 and 200 kg ha^{-1} $year^{-1}$) was used. Elevated CO_2 and N treatment had contrasting effects on the architecture of fine roots and their associated mycorrhizae. Elevated CO_2 increased both fine root extensity (degree of soil exploration) and intensity (extent that roots use explored areas) but had no effect on mycorrhizae. In contrast, N-fertilization had no effect on fine root extensity or intensity but increased mycorrhizal extensity and intensity. To better understand and model the responses of systems to increasing CO_2 concentrations and N deposition/fertilization it is necessary to consider these contrasting root architectural responses.

Trudell, S.A., P.T. Rygiewicz, and R.L. Edmonds. 2004. Patterns of nitrogen and carbon stable isotope ratios in macrofungi, plants and soils in two old-growth conifer forests. New Phytologist 164:317-335.

To further assess the usefulness of stable isotope ratios for understanding elemental cycling and fungal ecology, we measured δ 15 N and δ 13 C in ectomycorrhizal and saprotrophic macrofungi, plants, woody debris and soils from two old-growth conifer forests in Olympic National Park, Washington, USA. • Ecosystem isotope patterns were similar at the two forests, but differences existed that appear to reflect soil nitrogen availability and C allocation within the ectomycorrhizal symbioses. δ 15 N and δ 13 C of ectomycorrhizal and saprotrophic fungi differed in both forests, and a dual δ 15 N/ δ 13 C plot provided the best means of distinguishing them. Within both groups, δ 15 N and δ 13 C differed among genera and species, and the difference in species composition was an important determinant of the different overall δ 15 N of the ectomycorrhizal fungi at the two forests. • Variation in multiple ecophysiological traits such as organic N use, mycelial morphology and transfer of N to phytobionts appears to underlie the variation in the isotope signatures of ectomycorrhizal fungi. • The varied isotope signatures of ectomycorrhizal fungi suggest considerable functional diversity among them. Life-history strategies could provide a framework for interpreting these patterns.

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 microfungal 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.

CROP EFFECTS

Lee, J.J., D.L. Phillips and V.W. Benson. 1999. Soil erosion and climate change: assessing potential impacts and adaptation practices. Journal of Soil and Water Conservation 54:529-536.

Changes in climate associated with changes in atmospheric concentrations of CO_2 and other greenhouse gases might affect soil erosion by wind and water. Changes in erosion could in turn cause changes in productivity and sustainability of agricultural systems, and changes in air quality (PM_{10}) and water quality (sediment transport). Substantial effects on productivity may, however, only occur several decades after climate changes. This paper preserves a procedure for assessing the potential effects of climate change on erosion and productivity. A preliminary screening process is used to identify and prioritize regions and management systems. Subsequent simulation of selected sites with the EPIC model is used to investigate potential practices to adapt agricultural systems to climate change. In some cases, proposed adaptation strategies might reduce sustainability if they are not matched to environmental conditions found at specific sites. As an example, the assessment procedure is applied to evaluate vulnerability and adaptation practices for a 20% increase in mean monthly wind speeds in the U.S. corn belt.

Lee, Jeffrey J., Donald L. Phillips and Rusty F. Dodson. 1996. Sensitivity of the US corn belt to climate change and elevated CO_2: II. Soil erosion and organic carbon. Agricultural Systems 52:503-521.

Climate models indicate that increasing atmospheric concentrations of carbon dioxide and other greenhouse gases could alter climate globally. The EPIC (Erosion/Productivity Impact Calculator) model was used to examine the sensitivity of soil erosion (wind, water) and soil organic carbon (SOC) (15 cm and 1 m depth) across the US corn belt to changes in temperature (+ 2°C), precipitation (± 10%, ± 20%), wind speed (± 10%, ± 20%), and atmospheric CO_2 concentration (350, 625 ppmv). One-hundred-year simulations were run for each of 100 sites under 36 climate/CO_2 regimes. The100-year regionally aggregated mean water erosion rates increased linearly with precipitation, whereas the wind erosion rates decreased and total erosion rates increased non-linearly. Increasing temperature by 2°C (with CO_2 and mean wind speed held constant) decreased water erosion by 3-5%, whereas wind erosion increased by 15-18%. Total erosion increased with increased temperature. Increasing CO_2 from 350 to 625 ppmv (with temperature increased by 2°C and mean wind speed held constant) had no effect on water erosion, despite increases in annual total and peak runoff; this was attributed to increased vegetation cover. Wind erosion decreased by 4-11% under increased CO_2. Wind erosion was very sensitive to mean wind speed, increasing four-fold and decreasing 10-fold for a 20% increase or decrease in mean wind speed, respectively. This was attributed to a threshold effect. SOC to 1 m decreased 4.8 Mg-C ha^{-1} from an initial value of 18·1 Mg-C ha^{-1} during the 100-year baseline simulation. About 50% of this loss (2·3 Mg-C ha^{-1}) was due to transport offsite by soil erosion. SOC in the top 15 cm decreased 0·8 Mg-C ha^{-1} from an initial value of 4·9 Mg-C ha^{-1}. Increased temperature and precipitation accelerated these losses of SOC, whereas increased CO_2 slowed the losses.

Lee, J.J., D.L. Phillips and R. Liu, 1993. The effect of trends in tillage practices on erosion and carbon content of soils in the US corn belt. Water, Air, and Soil Pollution 70:389-401.

The EPIC model was used to simulate soil erosion and soil C content at 100 randomly selected sites in the US corn belt. Four management scenarios were run for 100 years: (1) current mix of tillage practices maintained; (2) current trend of conversion to mulch-till and no-till maintained; (3) trend to increased no-till; (4) trend to increased no-till with addition of winter wheat cover crop. As expected, the three alternative scenarios resulted in substantial decreases in soil erosion compared to the current mix of tillage practices. C content of the top 15 cm of soil increased for the alternative scenarios, while remaining approximately constant for the current tillage mix. However, total soil C to a depth of 1 m from the original surface decreased for all scenarios except for the no-till plus winter wheat cover crop scenario. Extrapolated to the entire US com belt, the model results suggest that, under the current mix of tillage practices, soils used for corn and/or soybean production will lose 3.2 x 10^6 tons of C per year for the next 100 years. About 21 % of this loss will be C transported off-site by soil erosion; an unknown fraction of this C will be released to the atmosphere. For the base trend and increased no-till trend, these soils are projected to lose 2.2 x 10^6 t-C yr^{-1} and 1.0 X 10^6 t-C yr^{-1}, respectively. Under the increased no-till plus cover crop scenario, these soils become a small sink of 0.1 x 10^6 t-C yr^{-1}. Thus, a shift from current tillage practices to widespread use of no-till plus winter cover could conserve and sequester a total of 3.3 x 10^6 t-C yr^{-1} in the soil for the next 100 years.

Leemans, Rik and Allen M. Solomon. 1993. Modeling the potential change in yield and distribution of the earth's crops under a wamed climate. Climate Research 3:79-96.

The large-scale distribution of crops is largely determined by climate. We present the results of a climate-crop prediction model based on the U.N. Food and Agriculture Organization crop-suitability approach, implemented in a GIS (geographic information system) environment using several global environmental databases. The model utilizes daily temperature and soil moisture conditions to determine the properties of the growing period. Crops are characterized by their variety-specific minimum growing period requirements and photosynthesis and respiration properties. Temperature and radiation during the growing period control the development of each crop. The model simulates crop-specific geographic distributions by demarcating the region where rain-fed productivity is possible. The model takes only non-irrigated crop productivity into account and the potential increase in productivity by technical means is not considered. The model therefore shows no potential yield in arid, irrigation-dependent regions. The simulated distributions of crops under current climatic conditions coincide largely with the current agricultural regions. Simulations with an atmospheric general circulation model (AGCM)-derived climate-change scenario illustrate changes in the agricultural potential. There are large regional differences in the response. Only high-latitude regions uniformly benefit f rom the climatic change with projected longer growing periods and an increased productivity. Most other regions, however, do not benefit significantly or even lose productivity after such change. In most of the latter regions differences in moisture availability control the change. The analysis shows that agricultural potential and impacts of climatic changes can be simulated comprehensively.

Phillips, Donald L., Jeffrey J. Lee and Rusty F. Dodson. 1996. Sensitivity of the US corn belt to climate change and elevated CO_2: I. Corn and soybean yields. Agricultural Systems 52:481-502.

Climate models indicate that increasing atmospheric concentrations of CO_2 and other greenhouse gases could alter climate globally. The EPIC (Erosion Productivity Impact Calculator) model was used to examine the sensitivity of corn and soybean yields over the US corn belt to changes in temperature, precipitation, wind, and atmospheric CO_2 concentration. A statistically representative sample of 100 corn and soybean production sites was selected from the 1987 National Resources Inventory (NRI). One--hundred-year simulations were run for each site under 36 different climate/CO_2 scenarios. The results were area weighted according to the NRI area expansion factors to produce a regionally aggregated estimate of yields. EPIC did an excellent job of reproducing current regional mean expected yields under the baseline scenario. There were 3% decreases in both corn and soybean yields in response to a 2°C temperature increase at baseline precipitation levels, with larger and smaller temperature effects under drier and wetter conditions, respectively. Crop yields increased and decreased in response to increases and decreases of 10% or 20% precipitation. A 10% precipitation increase roughly balanced the negative effect of the 2°C temperature increase. Whether the precipitation changes resulted from altered precipitation event frequency or amount per event had little effect on mean crop yields; however interannual yield variability was higher when precipitation decreases were due to frequency rather than intensity. The opposite was true, though to a lesser extent, for precipitation increases. Potential evapotranspiration responded linearly to changes in mean mind speed, leading to modest changes of 1-3 days of water stress per growing season, yield increases of up to 2% for decreased wind, and yield decreases of up to 6%.for increased wind. Elevated CO_2 concentrations of'625 ppmv gave the greatest yield increases, + 17% for corn and + 27% for soybean at baseline temperature and precipitation levels. The relative CO_2 effect was larger under drier conditions.

Phillips, D.L., D. White and C.B. Johnson. 1993. Implications of climate change scenarios for soil erosion potential in the USA. Land Degradation and Rehabilitation 4:61-72.

Atmospheric general circulation models (GCMS) project that increasing atmospheric concentrations of CO_2 and other greenhouse gases may result in global changes in temperature and precipitation over the next 40-100 years. Equilibrium climate scenarios from four GCMs run under doubled CO_2 conditions were examined for their effect on the climatic potential for sheet and rill erosion in the conterminous USA. Changes in the mean annual rainfall factor (*R*) in the Universal Soil Loss Equation (USLE) were calculated for each cropland, pastureland and rangeland sample point in the 1987 National Resources Inventory. Projected annual precipitation changes were assumed to be from differences in either storm frequency or storm intensity. With all other USLE factors held constant these changes in *R* translated to changes in the sheet and rill erosion national average of +2 to +16 per cent in croplands, -2 to + 10 per cent in pasturelands and -5 to +22 per cent in rangelands under the eight scenarios. Land with erosion rates above the soil loss tolerance (7) level and land classified as highly erodible (erodibility index >8) also increased slightly. The results varied from model to model, region to region and depended on the assumption of frequency *versus* intensity changes. These results show the range of sensitivity of soil erosion potential by water under projected climate change scenarios. However, actual changes in soil erosion could be mitigated by alterations in cropping patterns and other management practices, or possibly by increased crop growth and residue production under higher atmospheric CO_2 concentrations.

RICE EFFECTS

Bachelet, Dominique, Douglas Brown, Margi Böhm and Periann Russell. 1992. Climate change in Thailand and its potential impact on rice yield. Climatic Change 21:347-366.

In Thailand, the world's largest rice exporter, rice constitutes a major export on which the economy of the whole country depends. Climate change could affect rice growth and development and thus jeopardize Thailand's wealth. Current climatic conditions in Thailand are compared to predictions from four general circulation models (GCMs). Temperature predictions correlate well with the observed values. Predictions of monthly rainfall correlate poorly. Virtually all models agree that significant increases in temperature (from 1 to 7 °C) will occur in the region including Thailand following a doubling in atmospheric carbon dioxide (CO_2) concentration. The regional seasonality and extent of the rise in temperature varies with each model. Predictions of changes in rainfall vary widely between models. Global warming should in principle allow a northward expansion of rice-growing areas and a lengthening of the growing season now constrained by low temperatures. The expected increase in water-use efficiency due to enhanced CO_2 might decrease the water deficit vulnerability of dryland rice areas and could make it possible to slightly expand them.

Bachelet, Dominique, John Van Sickle and Cheryl A. Gay. 1992. The impacts of climate change on rice yield: evaluation of the efficacity of different modeling approaches. *In* International Symposium on Systems Approaches for Agricultural Development.

Increasing concentrations of carbon dioxide (CO_2) and other greenhouse gases are expected to modify the climate of the earth in the next 50-100 years. Mechanisms of plant response to these changes need to be incorporated in models that predict crop yield to obtain an understanding of the potential consequences of such changes. The objectives of this paper are (1) to review climate change predictions and their reliability, (2) to review the major hypotheses and/or experimental results regarding rice sensitivity to climate change and (3) to evaluate the suitability of existing rice models for assessing the impact of global climate change on rice production in the rice-growing areas of Asia. A review of physiologically-based rice models (CERES-Rice, MACROS, RICESYS) illustrates their potential to predict possible rice responses to elevated CO_2 and increased temperature. Both MACROS and CERES (wetland rice) responses to temperature and CO_2 agrees with recent experimental data from Baker et al.. (1990c). RICESYS is an ecosystem model which predicts herbivory and inter-species competition between rice and weeds but does not include CO_2 effects. Its response to increasing temperature also agrees with experimental findings. Models using empirical relationships between climate and yield have been used to predict country-scale changes following climate change. Their simplicity is an asset for continental-scale assessments but the climatic effects are often overshadowed by stronger technological or political effects. In conclusion, each modeling approach has its value. Researchers should choose or build the most appropriate model for their projects' objectives.

Bachelet, Dominique, Andrew Herstrom and Doug Brown. 1993. Rice production and climate change: design and development of a GIS database to complement simulation models. Landscape Ecology 8:77-91.

A cooperative project between the International Rice Research Institute in Los Baños, Philippines, and the U.S. EPA Environmental Research Laboratory in Corvallis, Oregon, was initiated to estimate how rice yield in Asia might be affected by future climate change and enhanced UV-B irradiance following stratospheric ozone depletion. A radiative transfer model was used to estimate daily UV-B irradiance levels using remotely sensed ozone and cloud cover data for 1274 meteorological stations. A rice yield model using daily climatic data and cultivar-specific coefficients was used to predict changes in yield under given climate change scenarios. This paper gives an overview of the data required to run these two models and describes how a geographical information system (GIS) was used as a data pre- or postprocessor. Problems in finding reliable datasets such as cloud cover data needed for the UV-B radiation model and radiation data needed for the rice yield model are discussed. Issues of spatial and temporal scales are also addressed. Using simulation models at large spatial scales helped identify weaknesses of GIS data overlay and interpolation capabilities. Even though we focused our efforts on paddy rice, the database is not intended to be system specific and could also be used to analyze the response of other natural systems to climatic change.

Bachelet, D. and H.U. Neue. 1991. Methane sources and sinks. Working Group Report, NATO Workshop on The Atmospheric Methane Cycle, Mt. Hood, Oregon, October 6-11, 1991.

Methane (CH_4) concentrations in the atmosphere have increased from about 0.75 to 1.7 ppmv since preindustrial times (Steele et al. 1987, Khalil and Rasmussen 1990). Lelleveld and Crutzen (1992) attribute the current annual rate of increase of about 0.8% year^{-1} to increases In industrial and agricultural emissions since some key natural sources (e.g. wetlands and marshes) have been reduced due to development pressure decreasing their area in various parts of the world. We have tried, in this chapter, to concisely summarize the discussions that took place at Timberline, October 8-10, 1991, to quantity the size of the global “Methane Sources and Sinks” that may contribute to the atmospheric increase. Several “specialty” groups emerged during the workshop and it is their conclusions that are presented here. Each paragraph is also the focus of an individual chapter and of usually several manuscripts that were submitted to Chemosphere. We have tried to cite these documents in the relevant sections and we refer the reader to these sources for detailed explanations of each source and sink.

Bachelet, D. and J.L. Mailander. 1992. Rice field inventory using AVHRR data. 13[th] Asian Conference on Remote Sensing, October 7-11, 1992, Ulaanbaatar, Mongolia.

Time series Normalized Difference Vegetation Index (NDVI) data, computed from Advanced Very High Resolution Radiometer (AVHRR) data, were used in a pilot study to locate areas of rice cultivation in the Unftod States of America (USA). The large size of rice fields and the relative phenological homogeneity of the rice growing regions in the US make them ideal sites for a pilot study. NDVI dynamics were examined using 16 km global area coverage satellite data from 1988. Unsupervised classification was used to distinguish rice fields from other vegetation cover types. The technique was used for California where the contrast between irrigated and natural vegetation is the most pronounced and later applied to Louisiana, Arkansas and Texas. Identical methods were used to classify the vegetation in China where the field size is much smaller and the cropping season more extended. The rice NDVI dynamics was most obvious where only one crop is grown and the growing season is limited by low winter temperatures. Areas where several crops are grown each year were more difficult to identffy. To effectively assess rice locations, the seasonal fluctuations of the crop, which are only partially dependent on seasonal precipitation because of irrigation, must be isolated from characteristics associated with natural vegetation and other irrigated crops.

Bachelet, Dominique and Cheryl A. Gay. 1993. The impacts of climate change on rice yield: a comparison of four model performances. Ecological Modelling 65:71-93.

Increasing concentrations of carbon dioxide (CO_2) and other greenhouse gases are expected to modify the climate of the earth in the next 50-100 years. Mechanisms of plant response to these changes need to be incorporated in models that predict crop yield estimates to obtain an understanding of the potential consequences of such changes. This is particularly important in Asia where demographic forecasts indicate that rice supplies worldwide will need to increase by 1.6% annually to the year 2000 to match population growth estimates. The objectives of this paper are (1) to review the major hypotheses and/or experimental results regarding rice sensitivity to climate change and (2) to evaluate the suitability of existing rice models for assessing the impact of global climate change on rice production. A review of four physiologically-based rice models (RICEMOD, CERESRice, MACROS, RICESYS) illustrates their potential to predict rice responses to elevated CO_2 and increased temperature. RICEMOD does not respond to increases in CO_2 nor to large increases in temperature. Both MACROS and CERES (wetland rice) responses to temperature and CO_2 agree with recent experimental data. RICESYS is an ecosystem model which predicts herbivory and inter-species competition between rice and weeds but does not respond to CO_2. Its response to increasing temperature also agrees with experimental data.

Matthews, R.B., M.J. Kropff and D. Bachelet. 1994. Climate change and rice production in Asia.

Rice is the second most important crop in the world after wheat, with about 522 million tonnes being produced from about 148 million hectares in 1990. The largest production of rice is from Asia, which produces about 94 per cent of the total world production. In this region, rice is the main item of the diet and provides an average of 35 per cent of the total calorific intake compared to only 2 per cent in the U.S. Rapid population growth is already placing increasing pressure on the rice-growing resources in the region, not only from the increased demand from a higher number of people to feed, but also from the encroachment of residential areas into rice growing areas. The effects of climate change only add to an already complex problem, even more so as rice cultivation itself has a significant effect on global warming through the emission of the greenhouse gas, methane. from decaying plant material in the water-logged paddy fields. There is clearly an urgent need to evaluate. the interaction between climate change and rice production in this region to provide a basis for decisions by policy make, agriculturalists, and environmentalists alike.

Moya, T. B., O. S. Namuco, L. H. Ziska, and D. Olszyk. 1998. Growth dynamics and genotypic variation in tropical field-grown paddy rice (*Oryza sativa* L.) with increasing carbon dioxide and temperature. Global Change Biology 4:645-656.

Increasing atmospheric concentrations of trace pollutants, especially carbon dioxide (CO_2) are expected by many leading scientists to result in increases in air temperature and associated changes in the global climate. Increasing CO_2 and temperature directly affect vegetation with potentially important impacts on critical world food crops. The EPA, in collaboration with the International Rice Research Institute in Los Baños, the Philippines, conducted a long-term study on the effects of increased CO_2 and temperature on tropical field-grown paddy rice, the most important food crop for a large portion of the world's population. Over four growing seasons, two wet and two dry, increased CO_2 alone increased grain yield. In contrast, increased temperature alone decreased grain yield. The combination of increased CO_2 and temperature resulted in a yield slightly less than with current ambient conditions. Comparison of the CO_2 and temperature results for several rice cultivars indicated differences in response which may be useful for adaptation of rice to a future climate. This results are vital for international assessments of the impacts of global change on the earth's resources.

Olszyk, D. M., H. G. S. Centano, L. H. Ziska, J. Kern, and R. Matthews. 1999. Global climate change, rice productivity and methane emissions: Comparison of simulated and experimental results. Agriculture and Forestry Meteorology 97:87-101.

Irrigated rice production in Asia is a major source of food for a large portion of the world's population, as well as a major anthropogenic source for the greenhouse gas methane. Potential impacts of global change (elevated CO_2 and/or temperature) can be predicted with simulation models, but experiments are necessary to determine whether these effects occur in the field. We compared key experimental results (grain yield, biomass, methane emissions) from experiments at the International Rice Research Institute at Los Baños, the Philippines; with simulation model predictions based on the climate data from those experiments. Comparisons covered three typical growing seasons, two dry (DS) and one wet (WS), with added data from an additional WS where growth was affected by a typhoon. Under current climate conditions (ambient CO_2 and temperature), potential yield from the ORYZA1 process model was the essentially the same as experimental grain yield in one DS, but 35% greater than experimental yield in the other seasons. Potential above ground biomass from ORYZA1 was close (-3 to +9%) to experimental above ground biomass in each season. The model generally predicted the increases in yield and above ground biomass found experimentally with elevated CO_2 alone, and small decreases to increases in yield and biomass with elevated temperature alone; but generally overestimated the magnitude of the changes. With both elevated CO_2 and elevated temperature, the model predicted a large increase in yield (+27%), compared with a slight decrease in yield (-4%) found in the experiments, across one WS and two DS. Model simulations of methane emissions with current climate corresponded to experimental results assuming 1.5% of the model total above and below ground biomass was emitted as methane. Model simulations of methane emissions with climate change scenarios generally agreed in direction but differed substantially in magnitude from the experimental results, as total plant biomass was not a good indicator of experimental methane emissions. This study demonstrated the usefulness of both experiments and models, and suggested ways of improving the models to predicting impacts of climate change on rice, such as by considering root biomass to predict methane emissions.

Olszyk, D., C. Wise and W.M. Weerakoon. 1993. Effects of CO_2 and temperature on five rice cultivars. J. Agr. Met. 48:787-790.

To obtain information for more detailed studies of how rice responds to climate change plants of three high tillering (IR30, IR52, IR74) and two low tillering cultivars (Azuceña and IRAT 104) were grown under controlled environment conditions for 28 days. To detect CO_2 responses, plants were grown at 400 μL L^{-1} (ambient) or 700 μL L^{-1} CO_2, at 31/26°C and a 13 hr photoperiod. To detect temperature responses, plants were grown at 28/22, 31/25, or 34/28°C light/dark temperatures, ambient CO_2, and a 13 hr photoperiod. Across all rice cultivars, a 300 μL L^{-1} increase in CO_2 stimulated root growth more than shoot growth ($p<0.05$), i.e. a 12 to 54% increase in root weight, 4 to 49% increase in total dry weight, and 10 to 32% increase in root/shoot ratio; but neither leaf nor stem weight and leaf or tiller number was affected by CO_2. In contrast, increasing temperature by 6°C for 28/22°C stimulated shoot but inhibited root growth, resulting in an increase ($p<0.05$) (38 to 69%) in leaf number but a significant decrease (32 to 48%) in root/shoot ratio and nonsignificant changes for other parameters. Cultivars responded similarly to CO_2 or temperature; there were no significant CO_2 x cultivar or temperature x cultivar interactions. However, rice cultivars responded differently to the same environment; IRAT 104 plants tended to have lower dry weights and tiller numbers than the IR cultivars with Azuceña as intermediate. Azuceña had lower root/shoot ratios than the other cultivars.

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Neue, Heinz-Ulrich, Lewis H. Ziska, Robin B. Matthews, Qiujie Dai. 1995. Reducing global warming - the role of rice. GeoJournal 35:351-362.

Activities to provide energy for an expanding population are increasingly disrupting and changing the concentration of atmospheric gases that increase global temperature. Increased CO_2 and temperature have a clear effect on growth and production of rice as they are key factors in photosynthesis. Rice yields could be increased with increased levels of CO_2, however, the rise Of CO_2 may be accompanied by an increase in global temperature. The effect of doubling CO_2 levels on rice production was predicted using rice crop models. They showed different effects of climate change in different countries. A simulation of the Southeast Asian region indicated that a doubling Of CO_2 increases yield, whereas an increase in temperature decreases yield.

Enhanced UV-B radiation resulting for stratographic ozone depletion has been demonstrated to significantly reduce plant height, leaf area and dry weight of two rice cultivars under glasshouse conditions. Data are still insufficient, however, for conclusive results on the effect of UV-B radiation on rice growth under field conditions.

Rice production itself has a significant effect on global warming and atmospheric chemistry through methane emission from flooded ricefields. Water regime, soil properties and the rice plant are major factors controlling the flux of methane in ricefields. Global and regional estimates of methane emission rates are still highly uncertain and tentative. Integration of mechanistic modeling of methane fluxes with geographic information systems of factors controlling these processes are required to improve estimates and predictions.

Weerakoon, Weerakoon M., David M. Olszyk and Dale N. Moss. 1999. Effects of nitrogen nutrition on responses of rice seedlings to carbon dioxide. Agriculture, Ecosystems and Environment 72:1-8.

Global atmospheric CO_2 concentration is increasing, likely increasing the productivity of crops as higher CO_2 enhances plant photosynthesis. Responsiveness to nitrogen supply is an essential trait of modern rice cultivars, and may play a role in the response of rice cultivars to higher CO_2. To determine the relationship between these two important production variables on young rice plants, seedlings of *Oryza sativa* L. 'IR72' and 'KDML 105' were exposed for 28 days after sowing to higher CO_2 levels of 373, 545, 723 and 895 µmol mol^{-1} and 3 levels of nitrogen fertility. There were large increases in leaf higher CO_2 assimilation and biomass production whereas leaf nitrogen concentration dropped sharply as higher CO_2 increased from 373 to 545 µmol mol^{-1}, with little additional effect from higher levels of higher CO_2. Root and shoot biomass, and tiller number per plant increased with increasing nitrogen supply and with increasing atmospheric higher CO_2 concentration. The biomass response to higher CO_2, was slight at low N supply, but became dramatically greater as the N supply increased. Mean root/shoot ratio increased slightly as atmospheric higher CO_2 concentration increased, but decreased sharply as nitrogen fertility rate increased. These results suggest that careful attention to nitrogen fertilization will be necessary for rice-farming to get the full benefit of any future increases in atmospheric higher CO_2.

UV-B EFFECTS ON RICE

Bachelet, D., P.W. Barnes, D. Brown and M. Brown. 1991. Latitudinal and seasonal variation in calculated ultraviolet-B irradiance for rice-growing regions of Asia. Photochemistry and Photobiology 54:411-422.

Ultraviolet-B (UV-B, 280-320 nm) irradiance was calculated for more than 1200 sites in Asia to characterize the spatial and temporal variation in the present UV-B climate for rice-growing regions. The analytical model of Green *et al.* (Photochem. Photobiol. 31:59-65, 1980) was used to compute UV-B irradiance for clear skies using satellite-observed ozone column thickness and local elevation data. Ground-based observations of cloud cover were then used to approximate the average effect of cloud cover on UV-B irradiance using the approach of Johnson *et al.* (Photochem. Photobiol. 23:179-188, 1976). Over the geographic range of rice cultivation, the maximum daily effective UVB irradiance (UV-B_{BE}), when weighted according to a general plant action spectrum, was found to vary approx. 2.5-fold under both clear and cloudy sky conditions. Under clear skies, the timing of maximum solar UV-B_{BE} changed with latitude and varied from February-March near the equator to July-August at temperate locations. Cloud cover was found to alter the season of maximum UV-B_{BE} in many tropical regions, due to the pronounced monsoonal climate, but had little effect on UV-B seasonality at higher latitudes. Under a climate resulting from a doubling of atmospheric carbon dioxide, estimated UV-B using predicted cloud cover was found to change by up to 17% from present conditions in Thailand. Both latitudinal and seasonal variation in solar UV-B radiation may be important aspects of the UV-B climate for rice as cultivars differ in sensitivity to UV-B and are grown under diverse conditions and locations.

Barnes, Paul W., Herman Gucinski and David Turner. 1989. Ecosystem responses to increases in solar Ultraviolet-B radiation. For presentation at the 82nd Annual Meeting and Exhibition, Anaheim, California, June 25-30, 1989.

Initial concern over a possible link between release between anthropogenic release of chlorofluorocarbons (CFCs) and stratospheric ozone depletion came in the early 1970's. There is now convincing evidence that CFCs and other substances are indeed contributing to ozone depletion. Ozone depletion has been found over the region of the South Pole as well as over mid-latitudes in the northern hemispheres. The recent detection of chlorine in the atmosphere above the arctic has increased concern over possible ozone depletion for this region as well. Stratospheric ozone depletion to therefore an issue of global importance.

Barnes, Paul W., Sharon Maggard, Steven R. Holman and Benito S. Vergara. 1993. Intraspecific variation in sensitivity to UV-B radiation in rice. Crop Science 33:1041-1046.

Twenty-two cultivars of rice (*Oryza saliva* L.) from diverse origins were grown under greenhouse conditions and exposed to ultraviolet-B radiation (UV-B; 280-320 nm) simulating a 5% reduction in stratospheric ozone in spring for the Philippines (14° N lat.) to evaluate growth and morphological responses to UV-B. In comparison to controls that received no UV-B, plants exposed to UV-B exhibited significantly reduced dry matter production (total plant and shoot), shoot height, leaf blade length and total leaf area, increased number of tillers, and greater weight fractions in leaf blades and roots. For most cultivars, the relative effects of UV-B on shoot morphology were greater than the effects on biomass production. The direction of the UV-B effects were generally similar for all cultivars, however, there were significant differences among cultivars in the magnitude of the UV-induced changes. Upland cultivars (IRAT104 and OS4) and two lowland cultivars commonly planted in the USA (Star Bonnet and Lemont) were found to be least affected by the UV-B, whereas modern, high yielding, lowland cultivars developed in the Philippines (IR52, IR35546-17-33, and IR58) were found to be among the most sensitive to UV-B. Our results indicate that in rice, as in other grasses, shoot morphology may be more responsive to solar UV-B change than plant productivity. Intraspecific variation in morphological responses to UV-B could contribute to difference among cultivars in susceptibility to UV-B-induced changes in competitive balance between rice and associated weeds of the rice agroecosystem.

Dai, Qiujie, Shaobing Peng, Arlene Q. Chavez, Ma. Lourdes L. Miranda, Benito S. Vergara and David M. Olszyk. 1997. Supplemental Ultraviolet-B Radiation Does Not Reduce Growth or Grain Yield in Rice. Reprinted from Agronomy Journal 89:793-799.

Negative effects of enhanced UV-B radiation have been demonstrated in plants, but impacts under realistic field conditions remain uncertain. Adverse impacts to major crops, such as rice (*Orvza saliva* L.), that are grown in areas with currently high ambient levels of UV-B, could have consequences for food security. To address the response of rice to UV-B, we conducted an intensive and extensive series of field experiments from 1992 to 1995 documenting the effects of supplemental UV-B (simulating approximately 20% ozone depletion for the Philippines), using irrigated rice cultivars under tropical conditions. This multiseason study indicated that supplemental UV-B had no significant effects on rice grain yield (including the yield components spikelet filling percentage, and 1000-grain weight) or growth parameters (plant height or panicles per square meter). The absence of UV-B effects was consistent across seasonal environment (four dry and three wet seasons), cultivar, and type of exposure system. Thus, rice yields are not likely to be affected by increases in UV-B under realistic field conditions.

Dai, Qiujie, Bin Yan, Shaobai Huang, Xiaozhong Liu, Shaobing Peng, M. Lourdes L. Miranda, Arlene Q. Chavez, Benito S. Vergara and David M. Olszyk. 1997. Response of oxidative stress defense systems in rice (*Oryza sativa*) leaves with supplemental UV-B radiation. Physiologia Plantarum 101:301-308.

The impact of elevated ultraviolet-B radiation (UV-B, 280-320 nm) on membrane systems and lipid peroxidation, and possible involvement of active oxygen radicals was investigated in leaves of two UV-B susceptible rice cultivars (*Oryza sativa* L. cvs IR74 and Dular). Rice seedlings were grown in a greenhouse for 10 days and then treated with biologically effective UV-B (UV-B_{BE}) radiation for 28 days. Oxidative stress effects were evaluated by measuring superoxide anion ($O_2^{\cdot}$ -) generation rate, hydrogen peroxide (H_2O_2) content. malondialdehyde (MDA) concentration and relative electrolyte conductivity (EC) for IR74 and Dular at 0 (control). 6 or 13 kJ m^{-2} day^{-1} UV-B_{BE}. Significant increases in these parameters were found in rice plants grown at 13 vs 0 kJ m^{-2} dav^{-1} UV-B_{BE} after 28 days; indicating that disruption of membrane systems may be an eventual reason for UV-B-induced injury in rice plants. There was a positive correlation between $O_2^{\cdot}$ - generation and increases in EC or MDA in leaves. Activities of enzymatic and nonenzymatic free radical scavengers were measured for IR74 after 7, 14. 21 and 28 days of exposure to 13 or 0 UV-B_{BE} to evaluate dynamics of these responses over time. Activities of catalase and superoxide dismutase , (but not ascorbate peroxidase) and concentrations of ascorbic acid and glutathione were enhanced by 13 vs 0 UV-B_{BE} after 14 days of UV-B exposure. Further exposure to 28 days of OV-B was associated with a decline in enzyme activities and ascorbic acid, but not glutathione. It is suggested that UV-B-induced injury may be associated with disturbance of active oxygen metabolism through the destruction and alteration of both enzymatic and nonenzymatic defense systems in rice.

Dai, Qiujie, Victoria P. Coronel, Benito S. Vergara, Paul W. Barnes and Arlene T. Quintos. 1992. Ultraviolet-B radiation effects on growth and physiology of four rice cultivars. Crop Science 32:1269-1274.

Enhanced ultraviolet-B (UV-B, 280-320 nm) radiation, such as could be caused by stratospheric O_3 depletion, has been demonstrated to profoundly affect plants. This study was conducted to determine the effects of UV-B on four high-yielding, lowland rice (*Oryza saliva* L.) cultivars (IR30, IR45, IR64, and IR74), and to evaluate morphological and physiological parameters for identifying sensitive and less-sensitive genotypes in future screenings. Ultraviolet-B radiation was supplied by UV-B-emitting fluorescent lamps in the phytotron. Plant height, leaf area, dry weight, net assimilation rate (NAR), and relative growth rate (RGR) were significantly influenced by 4-wk UV-B treatment in some cultivars. Based on the relative change in total biomass production between UV-B-irradiated and control plants, cultivar IR74 was the most sensitive and cultivar IR64 the least sensitive. Biomass production, however, did not proportionally decrease with plant height under UV-B treatment. Changes in plant height and leaf area induced by UV-B can alter the rice plant canopy structure. Differential varietal response was found in shoot dry weight, leaf area, specific leaf weight (SLW, NAR, and RGR. These parameters can be used as selection criteria for rice cultivars less sensitive to UV-B. Most physiological and biochemical parameters evaluated, including root-oxidizing activity, soluble protein, nucleic acid, ion leakage, stomatal aperture, and flavonoid and chlorophyll contents, were affected by 2 wk of UV-B treatment and gave differential cultivar responses. The distinct responses and relative ease in measurement of stomatal opening and ion leakage make these parameters suitable indices in selecting rice cultivars less sensitive to UV-B after 2 wk of UV-B treatment.

Dai, Qiujie, Shaobing Peng, Arlene Q. Chavez and Benito S. Vergara. 1994. Intraspecific responses of 188 rice cultivars to enhanced UVB radiation. Environmental and Experimental Botany 34:433-442.

Phytotron studies were conducted to determine the intraspecific variation in sensitivity of rice (*Oryza sativa* L.) to enhanced UVB and to test the hypothesis that rice cultivars originating from regions with higher ambient UVB radiation are more tolerant to enhanced UVB. Out of the 188 rice cultivars (from various rice growing regions and ecosystems) tested, 143 had significantly reduced plant height, 52 had smaller leaf area, 61 had lower plant dry weight and 41 had less tiller number under elevated UVB radiation (13.0 kJ m^{-2} day^{-1}) for 3 weeks. Six cultivars showed significant positive growth response to enhanced UVB radiation, although the mechanism is not clear at present. These six cultivars were from the summer rice crop of Bangladesh and from high elevation rice areas where prevailing UVB radiation is most likely to be greater. However, there was no correlation between the dry matter changes under enhanced UVB and the ambient UVB level at the origin of the cultivar across the 188 cultivars tested. Therefore, cultivars originating from regions with higher ambient UVB are not necessarily more tolerant to enhanced UVB radiation.

Olszyk, David, Quijie Dai, Paul Teng, Hei Leung, Yong Luo and Shaobing Peng. 1996. UV-B effects on crops: response of the irrigated rice ecosystem. Journal of Plant Physiology 148:26-34.

Increasing ultraviolet-B (UV-B) radiation resulting from depletion of the stratospheric ozone layer could have damaging effects on crops. This paper reviews recent findings on direct effects of UV-B on rice growth and yield as well as indirect effects via impacts on other organisms in the rice (*Oryza sativa*) agroecosystem. The findings are based on research by scientists at the International Rice Research Institute (IRRI) in Los Baños, the Philippines, and their collaborators in China and the United States; with comparison to research by scientists in other countries. Current results indicate that while enhanced UV-B directly impacts many aspects of rice growth, physiology, and biochemistry under controlled phytotron conditions; in general rice growth and yield are not affected under natural field conditions. The difference in response may be related both to the levels of UV-B exposure used in phytotron vs. field studies and the lower ratio of UV-A to UV-B in the phyrotron compared to field. In terms of indirect effects on rice blast disease, enhanced UV-B affected both the fungus itself (*Pyricularia grisea*) and the susceptibility of the rice plant to the fungus. Based on these data, simulation models estimated potential impacts of higher UV-B levels on blast severity and rice yield in different countries of southeast and east Asia. Ultimately, results from rice studies can be used to identify strategies to minimize any negative effects of UV-B on rice productivity.

Neue, Heinz-Ulrich, Lewis H. Ziska, Robin B. Matthews, Qiujie Dai. 2996. Reducing global warming - the role of rice. GeoJournal 35:351-362.

Activities to provide energy for an expanding population are increasingly disrupting and changing the concentration of atmospheric gases that increase global temperature. Increased CO_2 and temperature have a clear effect on growth and production of rice as they are key factors in photosynthesis. Rice yields could be increased with increased levels of CO_2, however, the rise Of CO_2 may be accompanied by an increase in global temperature. The effect of doubling CO_2 levels on rice production was predicted using rice crop models. They showed different effects of climate change in different countries. A simulation of the Southeast Asian region indicated that a doubling Of CO_2 increases yield, whereas an increase in temperature decreases yield.

Enhanced UV-B radiation resulting for stratographic ozone depletion has been demonstrated to significantly reduce plant height, leaf area and dry weight of two rice cultivars under glasshouse conditions. Data are still insufficient, however, for conclusive results on the effect of UV-B radiation on rice growth under field conditions.

Rice production itself has a significant effect on global warming and atmospheric chemistry through methane emission from flooded ricefields. Water regime, soil properties and the rice plant are major factors controlling the flux of methane in ricefields. Global and regional estimates of methane emission rates are still highly uncertain and tentative. Integration of mechanistic modeling of methane fluxes with geographic information systems of factors controlling these processes are required to improve estimates and predictions.

DATA BASES

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 $\pm$ 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.

Dodson, Rusty and Danny Marks. 1997. Daily air temperature interpolated at high spatial resolution over a large mountainous region. Climate Research 8:1-20.

Two methods are investigated for interpolating daily minimum and maximum air temperatures (T_{min} and T_{max}) at a 1 km spatial resolution over a large mountainous region (830 000 km^2) in the U.S. Pacific Northwest. The methods were selected because of their ability to (1) account for the effect of elevation on temperature and (2) efficiently handle large volumes of data. The first method, the neutral stability algorithm (NSA), used the hydrostatic and potential temperature equations to convert measured temperatures and elevations to sea-level potential temperatures. The potential temperatures were spatially interpolated using an inverse-squared-distance algorithm and then mapped to the elevation surface of a digital elevation model (DEM). The second method. linear lapse rate adjustment (LLRA), involved the same basic procedure as the NSA, but used a constant linear lapse rate instead of the potential temperature equation. Cross-validation analyses were performed using the NSA and LLRA methods to interpolate T_{min} and T_{max} each day for the 1990 water year, and the methods were evaluated based on mean annual interpolation error (IE). The NSA method showed considerable bias for sites associated with vertical extrapolation. A correction based on climate station/grid cell elevation differences was developed and found to successfully remove the bias. The LLRA method was tested using 3 lapse rates, none of which produced a serious extrapolation bias. The bias-adjusted NSA and the 3 LLRA methods produced almost identical levels of accuracy (mean absolute errors between 1.2 and 1.3°C), and produced very similar temperature surfaces based on image difference statistics. In terms of accuracy, speed, and ease of implementation, LLRA was chosen as the best of the methods tested.

TEMPERATURE, CO_2 AND O_3 EFFECTS

Andersen, Christian P. and Paul T. Rygiewicz. 1991. Stress Interactions and Mycorrhizal Plant Response: Understanding Carbon Allocation Priorities. Environmental Pollution 73:217-244.

In this paper, a framework is presented for studying responses of mycorrhiza to external stresses, including possible feedback effects which are likely to occur. The authors review recent literature linking carbon allocation and host/fungal response under natural and anthropogenic stress, and present a conceptual model to discuss how carbon may be involved in singular and multiple stress interactions of mycorrhizal seedlings. Due to an integral role in metabolic processes, characterizing carbon allocation in controlled laboratory environments could be useful for understanding host/fungal responses to a variety of natural and anthropogenic stresses. Carbon allocation at the whole-plant level reflects an integrated response which links photosynthesis to growth and maintenance processes.

A root-mycocosm system is described which permits spatial separation of a portion of extramatrical hyphae growing in association with seedling roots. Using this system, it is shown that root/hyphal respiratory release of pulse-labeled ^{14}C follows a sigmoidal pattern, with typical lag, exponential and saturation phases. Total respiratory release of ^{14}C per mg root and the fraction respired of total ^{14}C allocated to the root is greater in ponderosa pine inoculated with *Hebeloma crustuliniforme* than in noninoculated controls. Results illustrate the nature of information that can be obtained using this system. Current projects using the mycocosms include characterizing the dynamics of carbon allocation under ozone stress, and following the fate of organic pollutants. The authors believe that the system could be used to differentiate fungal- and host-mediated responses to a large number of other stresses and to study a variety of physiological processes in mycorrhizal plants.

Apple, Martha E., Melissa S. Lucash, David M. Olszyk, and David T. Tingey. 1998. Morphogenesis of Douglas-fir buds is altered at elevated temperature but not at elevated CO_2. Environmental and Experimental Botany 40:159-172.

Increases in atmospheric CO_2 and temperature are associated with global climate change. Scientists at the Western Ecology Division are investigating how these increases could affect the growth of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). This highly valued timber species is a dominant part of Pacific Northwest Ecosystems. During the four year experiment, seedlings were grown in sun-lit controlled environment chambers at ambient or elevated (+4° C above ambient) temperature, and at ambient or elevated (+200 ppm above ambient) CO_2. Elevated CO_2 had no effect on vegetative bud morphology, while the following unusual morphological characteristics were found in the elevated temperature treatment: rosetted buds with reflexed and loosened outer scales, convoluted inner scales, clusters of small buds, needles elongating between scales, needle primordia with white, hyaline apical extensions, and buds with hardened scales inside of unbroken buds. Buds became rosetted in elevated temperature chambers after temperatures exceeded 40°C in July. It appears that rosettes form after long-term exposure to elevated temperature and after shorter periods of exposure to intense heat. Elevated temperature influences bud morphology and may therefore influence the overall branching structure of Douglas-fir. These morphological changes could not only compromise timber production, but they could also affect ecosystem processes in Pacific Northwest forests.

Apple, M. E., M. S. Lucash, D. L. Phillips, D. M. Olszyk, and D. T. Tingey. 1999. Internal temperature of Douglas-fir buds is altered at elevated temperature. Environmental and Experimental Botany 41:25-30.

Douglas-fir saplings were grown in sun-lit controlled environment chambers at ambient or elevated (+4° C above ambient) temperature from 1993 until 1997. In the fall of 1996 and the winter of 1997, we measured the internal temperatures of vegetative buds with thermocouple probes to explore the possibility that differences in energy balance contribute to the formation of abnormal buds (rosetted with reflexed and loosened scales) buds at elevated temperature. We compared temperatures of: 1) rosetted buds with those of normal buds in elevated temperature chambers, 2) buds at ambient and elevated temperature, and 3) buds and air in elevated temperature chambers. We found that buds from elevated temperature chambers had higher temperatures than those from ambient temperature chambers, and that abnormal buds had higher and earlier peak daily temperatures than normal buds. Bud temperature tended to be higher than air temperature late in the day but lower than air temperature at night. Elevated temperature may influence the temperature balance of buds and contribute to development of abnormal buds.

Apple, Martha E., David M. Olszyk, Douglas P. Ormrod, James Lewis, Darlene Southworth, and David T. Tingey. 2000. Morphology and stomatal function of Douglas-fir needles exposed to climate change: elevated CO_2 and/or temperature. International Journal of Plant Sciences 161:127-132.

Climate change may impact the productivity of conifer trees by influencing needle morphology and function. to test the responses of needles to climatic variables, Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco saplings were grown in sun-lit controlled environment chambers at ambient or elevated CO_2 (+200 ppm above ambient) and at ambient or elevated temperature (+4EC above ambient). Needle characteristics evaluated included size (length, width, area), stomatal density (stomata/mm2), percent stomatal occlusion, and the quality of epicuticular wax. Needle function was evaluated as d loss of water through transpiration and as stomatal conductance to water vapor. Elevated CO_2 did not affect any needle parameters: either in terms of size, stomatal density, epicuticular wax, or needle function. In contrast, with elevated temperature needles were longer, had less finely granular epicuticular wax, and increased transpiration and stomatal conductance rates. These results indicate that elevated temperatures, but not elevated CO_2 associated with climate change may influence Douglas-fir needle structure and function, and hence, tree productivity.

Guak, Sunghee, David M. Olszyk, Leslie H. Fuchigami, and David T. Tingey. 1998. Effects of elevated CO_2 and temperature on cold hardiness and spring bud burst in Douglas-fir (*Pseudotsuga menziesii*). Tree Physiology 18:671-679.

Physiological adaptations of woody plants to stress could be significantly affected by climatic change, i.e., increasing atmospheric CO_2 concentration and air temperature. Cold hardiness was evaluated for Douglas-fir (*Psuedostuga menziesii*) seedlings grown in semi-closed, sun lit chambers with ambient or ambient plus 200 μmol mol^{-1} CO_2 and ambient or ambient or ambient plus 4°C air temperature. Needles were sampled on five dates from October 1995 to April 1996. Needles were frozen to a range of temperatures and rated for visible injury (browning). Cold hardiness was determined as the temperature for 50% injury “LT50". Elevated temperature delayed the times of both cold hardening of the trees in the fall and dehardening in the spring. At maximum cold hardiness (mid-January), elevated temperature trees were significantly less hardy compared to ambient temperature trees. Elevated CO_2 decreased cold hardiness compared to ambient CO_2 during both cold hardening and dehardening. The time of initial bud burst was affected by temperature treatment, but at the elevated temperature bud burst was erratic and terminal shoot growth poor compared to the ambient temperature possible due to disturbed dormancy and unsatisfied chilling requirements. Thus, in areas with currently mild winters such as western Oregon, climatic warming may disturb the physiological processes of dormancy and cold hardiness development; and lack of adequate chilling may affecting normal bud burst and subsequent vigorous shoot growth.

Hobbie, Eric. A., Jillian Gregg, David M. Olszyk, Paul T. Rygiewicz and David T. Tingey. 2002. Effects of climate change on labile and structural carbon in Douglas-fir needles as estimated by ß^{13} C and C_{area} measurements. Global Change Biology 8:1072-1084.

Models of photosynthesis, respiration, and export predict that foliar labile carbon (C) should increase with elevated CO_2 but decrease with elevated temperature. Sugars, starch, and protein can be compared beyween treatments, but these compounds make up only a fraction of the total labile pool. Moreover, it is difficult to assess the turnover of labile carbon betweeen years for evergreen foliage. Here, we combined changes in foliar C_{area} (C concentration on an areal basis) as needles aged with changes in foliar isotopic composition (ß^{13}C) caused by inputs of ^{13}C-depleted CO_2 to estimate labile and structural C in needles of different ages in a four-yea4, closed-chamber mesocosm experiment in which Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedlings were exposed to elevated temperature (ambient + 3.5□C) and CO_2 (ambient + 179 ppm).

Declines in ß^{13}C of needle cohorts as they aged indicated incorporation of newly fixed labile or structural carbon. The ß^{13}C calculations showed that new C was 41 ± 2% and 28 ± 3% of total needle carbon in second- and third-year, needles, respectively, with higher proportions of new C in elevated than ambient CO_2 chambers (e.g. 42 ± 2% vs. 37 ± 6%, respectively, for second-year needles). Relative to ambient CO_2, elevated CO_2 increased labile C in both first- and second-year needles. Relative to ambient temperature, elevated temperature diminished labile C in second-year needles but not in first-year needles, perhaps because of differences in sink strength between the two needle age classes. We hypothesis, that plant-soil feedbacks on nitrogen supply contributed to higher photosynthetic rates under elevated temperatures that partly compensated for higher, turnover rates of labile C. Strong positive correlations between labile C and sugar concentrations suggested that labile C was primarily determined by carbohydrates. Labile C was negatively correlated with concentrations of cellulose and protein. Ele-vated temperature increased foliar %C, possibly due to a shift of labile constituents from low %C carbohydrates to relatively high %C protein. Decreased sugar concentrations and increased nitrogen. concentrations with elevated temperature were consistent with this explanation. Because foliar constituents that vary in isotopic signature also vary in concentrations with leaf age or environmental conditions, inferences of c_i/c_a values from ß^{13}C of bulk leaf tissue should be done cautiously. Tracing of ^{13}C through foliar carbon pools may provide new insight into foliar C constituents and turnover.

Hobbie, E.A., D.M. Olszyk, P.T. Rygiewicz, D.T. Tingey and M.G. Johnson. 2001. Foliar nitrogen concentrations and natural abundance of ^{15}N suggest nitrogen allocation patterns of Douglas-fir and mycorrhizal fungi during development in elevated carbon dioxide concentration and temperature. Tree Physiology 21:1113-1122.

Pseudotsuga menziesii (Nfirb.) Franco (Douglas-fir) seedlings were grown in a 2 x 2 factorial design in enclosed mesocosms at ambient temperature or 3.5 °C above ambient, and at ambient C0$_2$ concentration [CO_2] or 179 ppm above ambient. Two additional mesocosms were maintained as open controls. We measured the extent of mycorrhizal infection, foliar nitrogen (N) concentrations on both a weight basis (%N) and area basis (N_{area}), and foliar δ^{15}N signatures (^{15}N/^{14}N ratios) from summer 1993 through summer 1997. Mycorrhizal fungi had colonized nearly all root tips across all treatments by spring 1994. Elevated [CO_2] lowered foliar %N but did not affect $N_{area,}$ whereas elevated temperature increased both foliar %N and N_{area}. Foliar δ^{15}N was initially -1% and dropped by the final harvest to between -4 and -5% in the enclosed mesocosms, probably because of transfer of isotopically depleted N from mycorrhizal fungi. Based on the similarity in foliar δ^{15}N among treatments, we conclude that mycorrhizal fungi had similar N allocation patterns across CO_2 and temperature treatments. We combined isotopic and N_{area} data for 1993-94 to calculate fluxes of N for second- and third-year needles. Yearly N influxes were higher in second-year needles than in third-year needles (about 160 and 50% of initial leaf N, respectively), indicating greater sink strength in the younger needles. Influxes of N in second-year needles increased in response to elevated temperature, suggesting increased N supply from soil relative to plant N demands. In the elevated temperature treatments, N effluxes from third-year needles were higher in seedlings in elevated [CO_2] than in ambient [CO_2], probably because of increased N allocation below ground. We conclude that N allocation patterns shifted in response to the elevated temperature and [CO_2] treatments in the seedlings but not in their fungal symbionts.

Hobbie,E.A., D.T. Tingey, P.T. Rygiewicz, M.G. Johnson, D.M. Olszyk 2002. Contributions of current year photosynthate to fine roots estimated using a ^{13}C-depleted CO_2 source. Plant and Soil 247: 233-242.

The quantification of root turnover is necessary for a complete understanding of plant carbon (C) budgets. A variety of techniques for quantification have been developed, including sequential coring, root in-growth cores, minirhizotron methods, nitrogen (N) budget methods, and C flux methods. We present an additional method to distinguish current- from prior-year allocation of carbon (C) to roots in global change experiments using changes in δ^{13}C resulting from application of tank-derived CO_2. In a four-year study examining effects of elevated CO_2 and temperature on reconstructed Douglas-fir (*Pseudotsuga mensiezii*) ecosystems, δ^{13}C patterns of fine roots and foliage were measured yearly. Native soil of low nitrogen (N) content was used, so plant N supply relied on natural soil N processes. Regression analyses showed that 75% of fine root C originated from current-year photosynthate, with no effects of elevated CO_2 or temperature under these N-limited conditions. The method is useful as an independent measure of the contribution of current-year photosynthate to root C and could be used to improve estimates of root C budgets with concurrent measurements of root C pools. We calculated an isotopic enrichment of root C relative to foliar C of 2‰. This enrichment agrees with prior measurements of the enrichment of heterotrophic versus autotrophic plant tissues and must be accounted for when using shifts in foliar δ^{13}C to calculate inputs of plant C into the soil. This enrichment is probably a contributing factor to the progressive enrichment in ^{13}C with increasing depth in soil profiles.

Homann, Peter S., Robert B. McKane and Phillip Sollins. 2000. Belowground processes in forest-ecosystem biogeochemical simulation models. Forest Ecology and Management 138:3-18.

Numerical simulation models of forest ecosystems synthesize a broad array of concepts from tree physiology, community ecology, hydrology, soil physics, soil chemistry and soil microbiology. Most current models are directed toward assessing natural processes or existing conditions, nutrient losses influenced by atmospheric deposition, C and N dynamics related to climate variation, and impacts of management activities. They have been applied mostly at the stand or plot scale, but regional and global applications are expanding. Commonly included belowground processes are nutrient uptake by roots, root respiration, root growth and death, microbial respiration, microbial mineralization and immobilization of nutrients, nitrification, denitrification, water transport, solute transport, cation exchange, anion sorption, mineral weathering and solution equilibration. Models differ considerably with respect to which processes and associated chemical forms are included, and how environmental and other factors influence process rates. Recent models demonstrated substantial discrepancies between model output and observations for both model verification and validation. The normalized mean absolute error between model output and observations of soil solution solute concentrations, solid phase characteristics, and process rates ranged from 0 to >1000%. There were considerable differences among outputs from models applied to the same situation, with process rates differing by as much as a factor of 4, and changes in chemical masses differing in both direction and magnitude. These discrepancies are attributed to differences in model structure, specific equations relating process rates to environmental factors, calibration procedures, and uncertainty of observations. Substantial improvement in the capability of models to reproduce observed trends is required for models to be generally applicable in public-policy decisions. Approaches that may contribute to improvement include modularity to allow easy alteration and comparison of individual equations and process formulations; hierarchical structure to allow selection of level of detail, depending on availability of data for calibration and driving variables; enhanced documentation of all phases of model development, calibration, and evaluation; and continued coordination with experimental studies.

Johnson, M. G., D. L. Phillips, D. T. Tingey, and M. J. Storm. 2000. Effects of elevated CO_2, N-fertilization, and season on survival of ponderosa pine fine roots. Canadian Journal of Forest Research 30:220-228.

Increasing carbon dioxide associated with global climate change may cause trees to live longer--at least their roots. EPA scientists in cooperation with scientists at the Desert Research Institute have completed a study on the effects of elevated carbon dioxide and nitrogen on the life span of Ponderosa pine fine roots. They found that fine roots of Ponderosa pines exposed to elevated atmospheric carbon dioxide lived longer. They used a minirhizotron camera system to observe the production and turnover of more than 3600 roots over 4 years and found that Ponderosa pine fine root production and survival were strongly influenced by season and seemed to be most strongly linked to soil temperature. Annual root production decreased with time, which suggests that root density reaches an optimal level that is likely constrained by site conditions. Assuming that longer-lived roots continue their resource acquisition functions, then elevated carbon dioxide may have the effect of extending the period of time that the root system can meet the resource demands of the shoot. Nitrogen fertilization decreased fine root life span. It seems that roots in resource-rich environments have shorter life spans than roots in resource-poor environments. Because uptake rates are lower in resource-poor soils, roots must function longer to meet the resource needs of the plant. Consequently, root life span is inversely related to the resource status of the soil.

Johnson, Mark G., David T. Tingey, Marjorie J. Storm and Donald L Phillips. 1995. Patterns of ponderosa pine fine root growth as affected by elevated CO_2: Initial field results. Plant Physiology 14:81-88.

The objective of this study is to determine whether the root growth of ponderosa pine *(Pinus ponderosa* Dougl. ex P. Laws. & C. Laws.) seedlings is affected by elevated atmospheric CO_2. Seeds were sown in native soil (May 1991) in open-top field exposure chambers at Placerville, CA and exposed to either ambient CO_2 (-350 μmol mol^{-1}) or two levels of elevated CO_2 (525 and 700 μmol mol^{-1}). The root systems were monitored 5 times over a seven month period (October 1992 through April 1993) using a minirhizotron camera system which permitted repeated observations of the root/soil environment. The lengths and diameters of all roots observed were measured and roots were assigned to one of 4 classes: new, white, brown, decaying. Occupancy, the presence or absence of roots, fungal hyphae, and mycorrhizae, was expressed by the proportions of minirhizotron frames in which roots, fungal hyphae, or mycorrhizae occurred. Root surface area density was expressed as the proportion of the total video image area that was covered by roots of any class, as well as the proportion covered by roots in each class. The majority (-95%) of the roots observed were smaller than 2 mm in diameter. Brown roots occurred most frequently. Root occupancy was highest in the Bw horizon. Root occupancy and mean root surface area density were highest in the elevated CO_2 treatments early in the study Over the course of the study, however, root occupancy and mean root surface area density in the ambient treatment increased until they were similar to the levels observed in the elevated CO_2 treatments. Overall, our results indicate that elevated CO_2 provided an early stimulation of root proliferation, however, after 7 months this initial stimulation did not persist.

Laurence, J. A., W. A. Retzlaff, J. S. Kern, E. H. Lee, W. E. Hogsett, and D. A. Weinstein. 2001. Predicting the regional impact of ozone and precipitation on the growth of loblolly pine and yellow-poplar using linked TREGRO and ZELIG models. Forest Ecology & Management 146:247-263.

To simulate the long-term effects of ozone on forests in the US, we linked TREGRO, a mechanistic model of an individual tree, to ZELIG, a forest stand model, to examine the response of forests to 5 ozone exposure regimes (0 to ~100 ppm h SUM06 per year) in 100 year simulations. TREGRO and ZELIG were parameterized using biological and meteorological data from three climate sites in the southeastern US. TREGRO was used to generate three-year exposure-response relationships between ozone and growth of loblolly pine *(Pinus tae*da L.) and yellow-poplar (*Liriodendron tulipifera* L.). Ratios (response at ozone exposure: response at base case) of total tree mass, leaf mass, and fine root/leaf mass were calculated and used to modify growth functions in ZELIG. At the end of the ZELIG simulation, the change in basal area of loblolly pine ranged from an increase of 44 percent to a decrease of 87 percent, depending on precipitation and ozone exposure. The basal area of yellow-poplar, simulated in competition with loblolly pine was not affected over most of its range. Over the range of the two species, the simulated changes in basal area due to ozone exposure were generally within ±10 percent of the base case. Competitive interactions between the species were not altered.

Lewis, J. D., M. Lucash, D. Olszyk, and D. T. Tingey. 2001. Seasonal patterns of photosynthesis in Douglas fir seedlings during the third and fourth year of exposure to elevated CO_2 and temperature. Plant, Cell and Environment 24:539-548.

Increases in atmospheric CO_2 and associated global warming may interact to affect on the rate of uptake of CO_2 into plants through the processes of photosynthesis, could affect overall tree productivity. Thus, we examined the interactive effects of elevated CO_2 and temperature on seasonal patterns of photosynthesis in Douglas-fir (*Psuedotsuga menziesii* (Mirb.) Franco) seedlings. Seedlings were grown in sunlit chambers controlled to track either ambient (~ 400 ppm) CO_2 or ambient + 200 ppm CO_2, and either ambient temperature or ambient + 4 °C. Light-saturated net photosynthetic rates were measured approximately monthly over a 21-month period. Elevated CO_2 increased net photosynthetic rates 21% on average across temperature treatments during both the 1996 hydrologic year, the third year of exposure, and the 1997 hydrologic year. Elevated mean annual temperature increased net photosynthetic rates 33% on average across CO_2 treatments during both years. Seasonal temperature changes also affected net photosynthetic rates. Across treatments, net photosynthetic rates were highest in the spring and fall, and lowest in July-August and December-January. Seasonal increases in temperature were not correlated with increases in the relative photosynthetic response to elevated CO_2. Seasonal shifts in the photosynthetic temperature optimum reduced temperature effects on the relative response to elevated CO_2. These results suggest that the effects of elevated CO_2 on net photosynthetic rates in Douglas-fir are largely independent of temperature.

Lewis, J.D., M. Lucash, D.M. Olszyk and D.T. Tingey. 2002. Stomatal responses of Douglas-fir seedlings to elevated carbon dioxide and temperature during the third and fourth years of exposure. Plant, Cell and Environment 25:1411-1421.

Two major components of climate change, increasing atmospheric [CO_2] and increasing temperature, may substantially alter the effects of water availability to plants through effects on the rate of water loss from leaves. To determine the interactive effects of elevated [CO_2] and temperature on seasonal patterns of water loss from Douglas-fir (*Pseudotsuga* *menziesii* (Mirb.) Franco) seedlings, we measured needle stomatal conductance, transpiration and instantaneous transpiration efficiency (ITE; □moles CO_2 assimilated per mole H_2O transpired. The seedlings were grown in sunlit chambers at either ambient CO_2 or ambient + 180 □mol mol^{-1} CO_2, and at ambient temperature or ambient + 3.5 °C. Needle gas exchange at the growth conditions was measured approximately monthly over 21 months. Across the study period, growth in elevated [CO_2] decreased transpiration rates an average of 12% and increased ITE an average of 46%. The absolute reduction of transpiration rates associated with elevated [CO_2] significantly increased with seasonal increases in vapour pressure deficit (VPD).

Growth in elevated temperature increased transpiration rates an average of 37%, and did not affect ITE. Combined, growth in elevated [CO_2] and elevated temperature increased transpiration rates an average of 19% compared to growth in ambient conditions. Stomatal sensitivity to VPD did not significantly vary between CO_2 or temperature treatments. This study suggested that climate change may substantially alter needle-level water loss and water use efficiency of Douglas-fir, but will not change stomatal sensitivity to VPD.

Lewis, J.D., D. Olszyk and D.T. Tingey. 1999. Seasonal patterns of photosynthetic light response in Douglas-fir seedlings subjected to elevated atmospheric CO_2 and temperature. Tree Physiology 19:243-252.

Increases in atmospheric CO_2 concentration and temperature are predicted to increase the light response of photosynthesis by increasing light-saturated photosynthetic rates and apparent quantum yields. We examined the interactive effects of elevated atmospheric CO_2 concentration and temperature on the light response of photosynthesis in Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) seedlings. Seedlings were grown in sunlit chambers controlled to track either ambient (-400 ppm) CO_2 or ambient + 200 ppm CO_2, at ambient temperature or ambient +4°C. Photosynthetic light response curves were measured over an 18-month period beginning 32 months after treatments were initiated. Light-response curves were measured at the growth CO_2 concentration, and were used to calculate the light-saturated rate of photosynthesis, light compensation point, quantum yield and respiration rate. Elevated CO_2 increased apparent quantum yields during two of five measurement periods, but did not significantly affect lightsaturated net photosynthetic rates, light compensation points or respiration rates. Elevated temperature increased all parameters. There were no significant interactions between CO_2 concentration and temperature. We conclude that down-regulation of photosynthesis occurred in the elevated CO_2 treatments such that carbon uptake at a given irradiance was similar across CO_2 treatments. In contrast, increasing temperature may substantially increase carbon uptake rates in Douglas-fir, assuming other environmental factors do not limit photosynthesis; however, it is not clear whether the increased carbon uptake will increase growth rates or be offset by increased carbon efflux through respiration.

Lin, Guanghui, J.R. Ehleringer, P.T. Rygiewicz, M.K. Johnson and D.T. Tingey. 1999. Elevated CO_2 and temperature impacts on different components of soil CO_2 efflux in Douglas-fir terracosms. Global Change Biology, 5:157-68.

Forests may be net sinks or sources of atmospheric CO_2, thereby mitigating or contributing to anthropogenic sources of CO_2. Increasing atmospheric [CO_2] or temperature stimulates soil respiration. However, no in situ techniques exist to partition respiration unambiguously into its sources [root respiration, and decomposition of litter and soil organic matter (SOM)]. The partitioning is possible using stable isotopes of carbon and oxygen. Soil respiration was partitioned while Douglas-fir seedlings were grown under four climate treatments. Under all treatments, litter decomposition contributed the most to respiration, followed by root respiration and then SOM decomposition. We show for the first time that increased respiration rates under climate treatments result from varying responses of the sources. The combined treatment of elevated [CO_2] and temperature enhanced respiration the most, and elevated [CO_2] alone the least. Respiration under elevated temperature was intermediate. Our results strongly suggest that, unless carbon influx to litter or SOM increases to offset enhanced carbon release from these sources, predicted global climate change may decrease long-term carbon storage in forest floors and soils.

Lin, Guanghui, Paul T. Rygiewicz, James R. Ehleringer, Mark G. Johnson, and David T. Tingey. 2001. Time-dependent responses of soil CO_2 efflux to elevated atmospheric [CO_2] and temperature in experimental forest mesocosms. Plant and Soil 229:259-270.

In order to balance terrestrial ecosystem carbon budgets under altered climates, it is necessary to know if soils will be net sources or sinks of carbon. Simply measuring the total amount of CO_2 released from soils (soil CO_2 efflux) has yielded conclusive evidence to address this question and numerous other questions concerning terrestrial ecosystem function since soil CO_2 efflux results from innumerable, interacting processes. One approach that may improve the reliability of using soil CO_2 efflux is to attribute the total efflux to its component sources. In general, soil CO_2 efflux results from respiration of plant roots and soil biota. Using a dual isotope method we developed previously, coupled with mixing models, we partitioned the efflux into the source components of 1) respiration from roots + rhizosphere (rhizosphere respiration is from organisms directly dependent on carbon substrates released from plant roots), 2) respiration from organisms decomposing the litter layer, and 3) respiration of organisms decomposing the soil organic matter (SOM). The partitioning was done for the Douglas-fir/soil system installed in the mesocosms at WED and subjected to four climatic treatments involving atmospheric CO_2 concentrations and temperatures. We partitioned the efflux for a two-year period to evaluate the stability of the sources to respond to the climate treatments. Total efflux was increased by elevated CO_2 or elevated temperature in both years, but the enhancement was much less in the second year. Rhizosphere respiration generally increased less in the climate treatments in the second year compared with the first year. Respiration due to litter decomposition also tended to increase less under elevated CO_2 in year two but there was no difference in the response to elevated temperature between the two years. In contrast, respiration due to SOM oxidation showed similar responses under elevated CO_2 in the two years but substantially less SOM oxidation occurred under elevated temperature in year two. Our results indicate that the plant/soil system responded rapidly but not consistently through time to the climate treatments. Some of the temporally-varying responses may have been due to the transient nature of physiological processes, while other variations may reflect effects of antecedent soil disturbance caused when the ecosystem was constructed in the mesocosms. Our results strongly indicate the need to conduct long-term (multi-year) projects of ecosystems in order to obtain reliable measures of their function when they are subjected to environmental stresses.

Olszyk, D.M., M.G. Johnson, D.T. Tingey, P.T. Rygiewicz, C. Wise, E. VanEss, A. Benson, M.J. Storm and R. King. 2003. Whole-seedling biomass allocation, leaf area, and tissue chemistry for Douglas-fir exposed to elevated CO_2 and temperature for 4 years. Can. J. For. Res. 33: 269-278.

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedlings were grown under ambient or elevated (ambient + 180 $\mu mol \cdot mol^{-1}$) CO_2 and ambient or elevated (ambient + 3.5°C) temperature in outdoor, sunlit chambers with a field soil. After 4 years, seedldings were harvested and measured for leaf area, leaf, fine root (<1 mm diameter), and structural (buds, branches, stems, main root, and lateral roots >1 mm in diameter) dry masses, and leaf and fine root C/N ratio, percent sugar, and percent cellulose. Elevated CO_2 did not affect biomass production or allocation for any plant organ but increased specific leaf mass, leaf C/N ratio, and percent sugar and decreased the ratio of leaf area to structural weight and leaf percent cellulose. Elevated temperature tended to reduce biomass allocation to leaves and leaf sugar concentration. Fine root percent sugar tended to increase with elevated temperature but only at elevated CO_2. Therefore, for Douglas-fir seedlings growing under naturally limiting soil moisture and nutrition conditions, elevated CO_2 and temperature may have little impact on biomass or leaf area except for reduced specific leaf mass with elevated CO_2 and reduced biomass allocation to leaves with elevated temperature. However, both elevated CO_2 and temperature may alter leaf chemistry.

Olszyk, D., M. Johnson, D. Tingey, G. King, M. Storm, and M. Plocher. 2003. Effects of carbon dioxide and ozone on growth and biomass allocation in *Pinus ponderosa*. Ekológia (Bratislava) 22: 265-276.

Future productivity of forests will be affected by combinations of elevated atmospheric CO_2 and O_3. Because productivity of forests will in part be affected by the growth of young trees, we evaluated shoot growth and whole-plant biomass responses of *Pinus ponderosa* seedlings to ambient and elevated levels of CO_2 and O_3. Elevated CO_2 increased stem diameters over the course of the study. At the final harvest, elevated CO_2 produced an increase in biomass for structural components of the seedlings, especially stems, buds, and 2-10 mm diameter roots, but not for other plant components. There was only a tendency for an increase in total plant biomass at the final harvest, and no significant O_3 effects or O_3XCO_2 interactions for any biomass components. This study indicated the potential for CO_2, but not O_3, effects on tree seedlings under realistic field conditions.

Olszyk, D. M., D. T. Tingey, L. Watrud, R. Seidler, and C. Andersen. 2000. Interactive effects of O_3 and CO_2: implications for terrestrial ecosystems *in*

Climate Change and Plants/Trace Gas Emissions and Plants. Singh et al., editors. Pp 97-136, Kluwer Academic Publishers, The Netherlands.

Ozone and CO_2 can have interactive effects on vegetation, with implications for terrestrial ecosystems. However, the combined impacts of both gases on vegetation are uncertain despite their co-occurrence. Thus, the objectives of this review are: (1) to evaluate the literature concerning interactive effects of O_3 and CO_2 on vegetation; and, (2) carry out this evaluation in the context of terrestrial ecosystem processes, i.e., carbon and nitrogen cycling. The literature indicates that: 1) there is no consistent interaction between O_3 and CO_2 on stomata; but an additive effect of O_3 and CO_2 which likely reduces the flux of both gases into leaves below the levels with the individual gases; 2) an increase in photosynthesis with elevated CO_2 may be canceled by a decrease in photosynthesis with high O_3; 3) elevated CO_2 inhibits $O_3$3 induced leaf injury ; and, 4) interactions between O_3 and CO_2 can interact to affect storage carbohydrates, leaf free radical metabolism, and allocation of C to shoots and roots. The nature of the interactions between O_3 and CO_2 vary with parameter, species and experiment. Furthermore, the mechanisms by which O_3 and CO_2 interact physiologically and metabolically are very uncertain. There is little information on effects of O_3 and CO_2 on other aspects of the belowground system such as root/rhizosphere processes, litter and soil microbes, and litter and soil physical and chemical properties. Intensive ecosystem-level studies are needed to determine the combined effects of O_3 and CO_2 on terrestrial vegetation, focusing of C and N cycling.

Olszyk, David, Claudia Wise, Erica VanEss, Martha Apple and David Tingey. 1998. Phenology and growth of shoots, needles, and buds of Douglas-fir seedlings with elevated CO_2 and/or temperature. Canadian Journal of Botany 76:1991-2001.

Increased atmospheric carbon dioxide and associated global warming may affect tree growth, but impacts of these combined stresses are largely unknown, especially over multiple growing seasons. Corvallis scientists studied the effects of elevated atmospheric carbon dioxide and elevated temperature associated with predicted global warming on Douglas-fir. Seedlings were grown for three full growing seasons in outdoor sun-lit chambers which maintained diel and seasonal variation in climate. Elevated carbon dioxide had no impact on overall phenology and growth of terminal shoots, needles, or buds. In contrast, elevated temperature affected phenology and growth compared to ambient temperature, i.e., main-flushes occurred slightly earlier in the spring, overall shoot and needle growth rates were higher earlier during the season, final terminal shoot length was reduced, and final needle length was either reduced, increased, or unchanged depending on season. The lammas-flush was delayed and/or decreased at elevated temperature. Leading terminal bud break and growth occurred earlier, resting winter bud length was reduced, and bud width tended to increase with elevated temperature. Thus, at least during seedling growth, elevated temperatures associated with global warming may reduce both main and lammas-flush growth, thereby altering tree productivity; whereas elevated carbon dioxide does not affect growth at either the current or elevated temperature.

Olszyk, David, Claudia Wise, Erica Van Ess, and David Tingey. 1998. Elevated temperature but not elevated CO_2 affects stem diameter and height of Douglas-fir seedlings: results over three growing seasons. Canadian Journal of Forest Research 28:1046-1054.

Global climatic changes may produce dramatic changes in forest productivity over the next century, but data are lacking to evaluate potential impacts of key aspects of global change, elevated temperature and CO_2, on tree growth. Thus at Corvallis the EPA is carrying out a long term study on the response of Douglas-fir [*Pseudotsuga menziessii* (Mirb.) Franco] trees to elevated CO_2 (+200 μmol mol^{-1}) and/or elevated temperature (+4 C). Seedlings were grown for three complete growing seasons in outdoor, sun-lit chambers. To simulate Oregon field growing conditions, trees received a wet-dry season cycle of soil moisture and relied on soil biological processes for nutrients. Elevated temperature advanced the date of initiation of shoot growth during each growing season: stem diameter and height began to increase earlier and stopped increasing earlier compared to trees grown at ambient temperature. At the end of the three seasons, elevated temperature resulted in significantly shorter trees at the elevated compared to the ambient temperature trees; but temperature had no effect stem diameters. Elevated CO_2 had no effect on either stem diameter or height at any time and there was no evidence for any CO_2 x temperature interactions. Thus, at least during early growth under field-like soil moisture and fertility conditions, elevated temperatures associated with global warming may reduce shoot height, but not necessarily stem diameter, suggesting a shift in allocation of above-ground biomass from canopy to stems with implications for competition during seedling establishment and for modeling tree growth. In contrast, elevated CO_2 may not affect at least early seedling shoot growth as measured by stem diameter or height.

Ormrod, D. P., V. G. Lesser, D. M. Olszyk, and D. T. Tingey. 1999. Elevated Temperature and carbon dioxide affect chlorophylls and carotenoids in Douglas-fir seedlings. International Journal of Plant Science 160:529-534.

Increased atmospheric carbon dioxide and associated global warming may affect tree growth, but the physiological mechanisms responsible for such changes are uncertain. Pigment analyses are widely used to evaluate plant vigor. When combined with needle sampling, pigment analyses provide rapid, inexpensive, and non-destructive data on plant stress. Additionally, plant pigments are readily measured using aircraft and satellite sensors. Corvallis scientists studied the effects of elevated atmospheric carbon dioxide and air temperature on needle pigments of Douglas-fir trees. Elevated carbon dioxide reduced pigment concentrations in current year needles. In contrast, elevated temperature was associated with increases in pigments concentrations in both current and previous year needles. Needle pigments were found to be responsive to temperature stress and enhanced atmospheric carbon dioxide. Consequently, needle and leaf pigments could provide a useful indicator of climate-related ecosystem stress.

Rygiewicz, Paul T. and Christian P. Andersen. 1994. Mycorrhizae alter quality and quantity of carbon allocated below ground. Nature 369:58-60.

Plants and soils are a critically important element in the global carbon-energy equation. It is estimated that in forest ecosystems over two-thirds of the carbon is contained in soils and peat deposits'. Despite the importance of forest soils in the global carbon cycle, fluxes of carbon associated with fundamental processes and soil functional groups are inadequately quantified, limiting our understanding of carbon movement and sequestration in soils. We report here the direct measurement of carbon in and through all major pools of a mycorrhizal (fungus-root) coniferous seedling (a complete carbon budget). The mycorrhizal symbiont reduces overall retention of carbon in the plant-fungus symbiosis by increasing carbon in roots and below-ground respiration and reducing its retention and release above ground. Below ground, mycorrhizal plants shifted allocation of carbon to pools that are rapidly turned over, primarily to fine roots and fungal hyphae, and host root and fungal respiration. Mycorrhizae alter the size of below-ground carbon pools, the quality and, therefore, the retention time of carbon below ground. Our data indicate that if elevated atmospheric CO_2 and altered climate stressors alter mycorrhizal colonization in forests, the role of forests in sequestering carbon could be altered.

Rygiewicz, Paul T., Mark G. Johnson, Lisa Ganio, David T. Tingey, and Marjorie J. Storm. 1997. Lifetime and temporal occurrence of ectomycorrhizae on ponderosa pine (*Pinus ponderosa* Laws.) seedlings grown under varied atmospheric CO_2 and nitrogen levels. Plant and Soil, 275-87.

A significant unanswered question concerning the global carbon (C) cycle and climate change is the fate of the “missing” C. Speculation attributes storage of this C to one or more of several sinks. In terrestrial ecosystems, a major storage pool for C is the soil. Carbon fixed aboveground eventually enters the soil via root and rhizosphere processes. Mycorrhizae as C sinks in the rhizosphere, are among the first soil biota to receive C fixed aboveground, and thereby greatly influence C dynamics in soil ecosystems. One step in this C release is via fine root and mycorrhizal turnover. It is necessary to know the lifespan and seasonal occurrence of roots and mycorrhizae to determine C flux into the soil, and the capacity of the soil ecosystem to sequester C. Seasonal occurrence and the lifespan of ectomycorrhizae of ponderosa pine (*Pinus ponderosa* Laws) grown under three levels each of atmospheric CO_2 concentration and annual nitrogen (N) additions were followed on a two-month frequency for 18 months using minirhizotron tubes and camera. The frequency of mycorrhizal root tips increased with carbon dioxide concentration while the lifespan of mycorrhizal root tips was not affected by carbon dioxide or nitrogen additions. Previous research on fine roots without mycorrhizae concluded that increases in carbon dioxide and nitrogen shortened the lifespan of fine roots, i.e., increased the turnover rate and subsequent release of carbon dioxide into the atmosphere. This research shows that mycorrhizae appear to provide some protection or buffering against changes in the root environment. If trees increase their frequency of mycorrhizal symbiosis under elevated CO_2, effects of environmental conditions (nutrients, etc.) that influence root turnover and C storage may be lessened. A very large flux of C moves through the mycorrhizal symbionts into soil, and much of that C is readily transformed into compounds that ultimately enter the soil organic matter pool, or are released to the atmosphere via soil respiration. This is the first published report on mycorrhizal tip lifespan with respect to CO_2 and N, and suggests that results found for nonmycorrhizal tips should not be universally applied to tree root systems when estimating carbon flux. If scientists estimating biospheric feedbacks of carbon dioxide from global warming assume that all forests behave the same with regard to mycorrhizae and carbon processing, and that the effects of CO_2 and N found for nonmycorrhizal root tips are universal, then projections of carbon flux may be wrong.

Rygiewicz, Paul T., Kendall J. Martin and Amy R. Tuininga. 2000. Morphotype community structure of ectomycorrhizas on Douglas-fir (*Pseudotsuga* menziesii Mirb. Franco) seedlings grown under elevated atmospheric CO_2 and temperature. Oecologia, 124:299-308.

Mycorrhizas, a symbiosis between the roots of plants and fungi, alter the carbon economy and nutrient uptake capabilities of plants, their regeneration, and the nutrient cycling and sustainability of ecosystems. During 1993-1997, scientists assessed how climate change stresses affected the abundance of the symbiosis, and the diversity of the fungi forming the symbiosis under altered climate conditions. The individual and interactive effects of elevated atmospheric CO_2 and temperature were assessed [ambient atmospheric CO_2 concentration, elevated CO_2 (200 ppm above ambient), ambient temperature, and elevated temperature (4 °C above ambient)]. In 1993, two-year-old Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) seedlings were planted in environment-tracking chambers (terracosms) containing reconstructed, native forest soil. We categorized the ectomycorrhizal (ECM) root tips into morphotypes using their gross morphological traits. A highly diverse and stable community of ectomycorrhizas was established in the terracosms (a total of 40 morphotypes was encountered during the experiment). When we considered the morphotype community in its entirety, we did not find large changes in its diversity (Simpson's index) due to climate treatments. While some morphotypes were negatively affected seasonally by higher temperatures (*Rhizopogon* spp. group), others (*Cenococcum* sp.) seemed to thrive. Underlying the dominant patterns of change in diversity, the subdominant populations responded slightly differently. Community diversity increased at a greater rate for all subdominant populations than the rate of increase of diversity over time when dominant populations were included in the community. Overall, disturbance by climate change seems to affect the symbiosis differentially, with the level of the symbiosis primarily affected by CO_2 and the proportions of individual fungal species forming the symbiosis primarily affected by temperature. Such results have implications on whether this obligate symbiosis can be maintained as the geographic distribution of trees species changes as future climate is altered.

Rygiewicz, P.T., K.J. Martin and A.R. Tuininga. 1997. Global Climate Change and Diversity of Mycorrhizae *in* Progress in Microbial Ecology, Martins, M.T., M.I.Z. Sato, J.M. Tiedje, L.C. N .Hagler, J. Döbereiner and P.S. Sanchez, editors. Pp 91-98.

We discuss elevated CO_2 and temperature effects on ectomycorrhizal diversity during the first part of a 3-4 year exposure using Douglas-fir seedlings. Ectomycorrhizae (ECM) are sorted into morphotypes by gross morphology. Number of ECM tips and number of morphotypes increased as exposure progressed indicating adjustment from nursery to native soil. Treatments may affect numbers of tips in the *Rhizopogon* morphotvpes differentialy by season. Simpson's index changed by season and was affected by temperature. Morphotype diversity as the exposure continues may affect dominance of the *Rhizopogon sp.* group. Treatment effects on specific root length, and ECM tip and morphotvpe numbers did not correspond so this aspect of C allocation may not influence colonization.

Tingey, David T., Mark G. Johnson, Donald L. Phillips, Dale W. Johnson and J. Timothy Ball. 1996. Effects of elevated CO_2 and nitrogen on the synchrony of shoot and root growth in ponderosa pine. Tree Physiology 16:905-914.

We monitored effects of elevated CO_2 and N fertilization on shoot and fine root growth of *Pinus pondrosa* Dougl. ex P. Laws. and C. Laws. grown in native soil in open-top field-exposure chambers at Placerville, CA, over a 2-year period. The experimental design was a replicated 3 x 3 factorial with the center treatment missing; plants were exposed to ambient (-365 μmol mol^{-1}) air or ambient air plus either 175 or 350 μmol mol^{-1} CO_2 in combination with one of three rates of N addition (0, 100 or 200 kg ha^{-1} $year^{-1}$). All CO_2 by N interactions were nonsignificant. Both the CO_2 and N treatments increased plant height, stem diameter and leaf area index (LAI). Elevated CO_2 increased fine root area density and the occurrence of mycorrhizae, whereas N fertilization increased coarse root area density but had no effect on fine root area density. Spring flushes of shoot height and diameter growth were initiated concurrently with the increase in new root area density but height and diameter growth reached their maxima before that of fine roots. The temporal patterns of root and shoot growth were not altered by providing additional CO_2 or N. Greatest root loss occurred in the summer, immediately following the period of greatest new fine root growth. Elevated N initially reduced the fine root area density/LAI ratio independently of CO_2 treatment, indicating that the relationship between fine roots and needles was not changed by CO_2 exposure.

Tingey, David T., Mark G. Johnson, Donald L. Phillips and Marjorie J. Storm. 1995. Effects of elevated CO_2 and nitrogen on ponderosa pine fine roots and associated fungal components. Journal of Biogeography 22:281-287.

The effects of CO_2 and nitrogen treatments on ponderosa pine *(Pinus ponderosa* Dougl. ex P. Laws. & C. Laws.) fine roots and associated fungal structures were monitored for a year (October 1992 to October 1993) using a minirhizotron camera system. The trees were grown in native soil in open-top field-exposure chambers at Placerville, CA and exposed to ambient (- 350 μmol mol^{-1}) air or ambient air plus either 175 or 350 μmol mol^{-1}) CO_2 and three levels of nitrogen addition (0, 100 and 200 kg ha^{-1}); however, the 100 kg ha^{-1} N treatment at ambient plus 175 μmol mol^{-1} CO_2 treatment was omitted from the experimental design. Roots were classified as new, white, brown, decaying or missing and their lengths and diameters measured. The occurrence of mycorrhizae and fungal hyphae was also recorded. The majority (> 90%) of roots observed were smaller than 2 mm and the mean diameter decreased during the study. None of the root parameters measured showed a significant response to elevated CO_2. The elevated CO_2 treatments consistently showed an increase in root area density averaging 50% larger compared to ambient CO_2, but this response was not statistically significant due to the high spatial variability of root distribution. Only new root area density showed a significant nitrogen response. The most new roots were initiated between April and June and the highest level of root loss occurred between June and August. The occurrence of mycorrhizae and fungal hyphae increased in response to CO_2 treatment but not the nitrogen. Their highest levels of occurrence were during August and October 93.

Tingey, David T., John A. Laurence, James A. Weber, Joseph Greene, William E. Hogsett, Sandra Brown and E. Henry Lee. 2001. Elevated CO_2 and temperature alter the response of *Pinus ponderosa* to ozone: a simulation analysis. Ecological Applications 11:1412-1424.

We investigated the potential impact of projected future temperature and CO_2 concentrations in combination with tropospheric O_3 on the annual biomass increment of *Pinus ponderosa* Doug. ex Laws. TREGRO, a process-based whole-tree growth model in which trees experienced a seasonal drought, was used to study the interactions of CO_2, temperature, and O_3 on tree growth along a latitudinal gradient in California, Oregon, and Washington, USA. The annual biomass increment increased in proportion to CO_2 concentration, although the magnitude varied among sites. Increasing air temperature (+ 1.3°C) increased growth at most sites. Elevated CO_2 increased the temperature optimum for growth at four sites and decreased it at two sites. The annual biomass increment decreased with increasing O_3 exposure. The differences in O_3 effects among sites were primarily controlled by differences in precipitation. Although increasing CO_2 can reduce the O_3 impact, it does not eliminate the impact of O_3. Elevated CO_2 would enhance tree growth more if O_3 exposures were reduced, especially in the more polluted sites. The greatest benefit for tree growth would come from reducing O_3 exposures in the most polluted sites, but we must also consider locations that have high inherent O_3 sensitivity because of their mesic conditions. Limiting the increase of O_3 levels in those areas will also increase tree growth.

Tingey, David T., Bruce D. McVeety, Ron Waschmann, Mark G. Johnson, Donald L. Phillips, Paul T. Rygiewicz, and David M. Olszyk. 1996. A versatile sun-lit

controlled-environment facility for studying plant and soil processes. J. Environ. Qual. 25:614-625.

A new environmental-tracking, sun-lit controlled-environmental facility (terracosm) that can control and manipulate climatic and edaphic factors while maintaining natural environmental variability was developed to study the effects of environmental stresses on a model ecosystem.

Tingey, David T., Donald L. Phillips, and Mark G. Johnson. 2000. Elevated CO_2 and conifer roots: effects on growth, life span and turnover. New Phytologist 147:87-103

WED scientists completed a review of the effects of elevated CO_2 on conifer roots for an invited presentation at an International Symposium, "Root Dynamics and Global Change: An Ecosystem Perspective" sponsored by New Phytologist and Global Change and Terrestrial Ecology (GCTE). The review concluded. That elevated CO_2 increases root growth and fine (diameter 2 mm) root growth across a range of species and experimental conditions. However, there is no clear evidence that elevated CO_2 changes the proportion of C allocated to roots, measured as either the root/shoot ratio or the fine root/needle ratio. Elevated CO_2 tends to increase mycorrhizal infection, colonization and the number of mycorrhizae and extramatrical hyphae, supporting its key role in aiding the plant to more intensively exploit soil resources. Only two studies have determined the effects of elevated CO_2 on conifer fine root life span and there is no clear trend. Although data are limited, elevated CO_2 increases the absolute fine root turnover rates in conifers. However, the standing crop root biomass is also higher, and the effect of elevated CO_2 on relative turnover rates (turnover/biomass) runs the gamut from an increase to a decrease. This review provides important data for assessing the ecological consequences of elevated CO_2 on coniferous forests.

Tingey, David T., Donald L. Phillips, Mark G. Johnson, Marjorie J. Storm, and J. Timothy Ball. 1997. Effects of elevated CO_2 and N-fertilization on fine root growth and mortality of *Pinus ponderosa*. Environmental and Experimental Botany 37: 3-83.

The effects of elevated CO_2 and N-fertilization on shoot and fine root growth of *Pinus ponderosa* Dougl. ex P. Laws. C. Laws. grown in native soil in open-top field-exposure chambers at Placerville, CA were monitored for a two-year period using minirhizotrons. The experimental design was a replicated 3 x 3 factorial with the center treatment missing; plants were exposed to ambient (~365 μmol mol^{-1}) air or ambient air plus either 175 or 350 μmol mol^{-1} CO_2 and 3 levels of N addition (0, 100 and 200 kg ha^{-1} yr^{-1}). The CO_2 by N interactions were not significant. By the second year, elevated CO_2 increased fine root occurrence, root length, root intensity and rooting depth compared to ambient CO_2 while N fertilization had no effect. Fine root mortality was increased by N fertilization but was reduced in elevated CO_2. Highest mortality occurred during summer and the lowest during winter. Elevated CO_2 initially increased mycorrhizal and fungal occurrence. Spring flushes of shoot height and diameter growth were initiated concurrently with the increase in new fine root growth. Initially, elevated N decreased the fine root length/LAI ratio but the effect did not continue. The fine root length/LAI ratio was similar among CO_2 treatments, indicating that the relationship between fine roots and needles was not changed by CO_2 exposure.

Tausz, M., D.M. Olszyk, S. Monschein, and D.T. Tingey. 2004. Combined effects of CO_2 and O_3 on antioxidative and photoprotective defense systems in needles of ponderosa pine. Biologia Plantarum 48 (4): 543-548.

Ponderosa pine seedlings were exposed to ambient or elevated carbon dioxide, combined with low or elevated tropospheric ozone. Ozone reduces needle contents of chlorophyll a and b, and ascorbate, and resulted in a more oxidized total ascorbate and a more de-epoxidized xanthophyll cycle pool irrespective of the CO_2 level. Trees under elevated CO_2 had a more oxidized glutathione pool and lower chlorophyll a content. There were no interactive effects between elevated CO_2 and elevated O_3 on any of the parameters measured; the results suggest that elevated atmospheric CO_2 concentrations do not compensate for ozone stress by increasing antioxidative capacity in ponderosa pine.

Vose, J. M., K. J. Elliott, D. W. Johnson, D. T. Tingey, and M. Johnson. 1997. Soil respiration response to two years of elevated CO_2 and N fertilization in ponderosa pine (*Pinus ponderosa* Doug. ex Laws.). Plant and Soil 190:19-28.

Scientists at WED recently completed a cooperative study with colleagues from the USFS and Desert Research Institute to determine the effects of elevated CO_2 and N fertilization on Ponderosa pine and associated rhizopshere processes. Elevated CO_2 treatment significantly increased the evolution of CO_2 from the soil; rates increased in relation to the CO_2 exposure level. The increased rates of soil CO_2 efflux indicate that rhizosphere processes such as root respiration or fungal respiration (i.e., decomposition) are increased by elevated CO_2. The soil CO_2 efflux rates were linearly related to the occurrence of fungi in the soil but unrelated to the occurrence of fine roots showing the fungal processes in the rhizosphere were the major biological factors controlling soil CO_2 efflux.

Vose, James M., Katherine J. Elliott, Dale W. Johnson, Roger F. Walker, Mark G. Johnson and David T. Tingey. 1995. Effects of elevated CO_2 and N fertilization on soil respiration from ponderosa pine *(Pinus ponderosa)* in open-top chambers. Canadian Journal of Forest Research 25:1243-1251.

We measured growing season soil CO_2 evolution under elevated atmospheric CO_2 and soil nitrogen (N) additions. Our objectives were to determine treatment effects, quantify seasonal variation, and determine regulating mechanisms. Elevated CO_2 treatments were applied in opentop chambers containing 3-year-old ponderosa pine

(Pinus ponderosa Dougl. ex Laws.) seedlings. Nitrogen applications were made annually in early spring. The experimental design was a replicated factorial combination of CO_2 (ambient, + 175, and + 350 µL L^{-1} CO_2) and N (0, 10, and 20 g.m^{-2} N as ammonium sulfate). Soils were irrigated to maintain soil moisture at >25%. Soil CO_2 evolution was measured over diurnal periods (20-22 h) in April, June, and October 1993 using a flow-through, infrared gas analyzer measurement system. To examine regulating mechanisms, we linked our results with other studies measuring root biomass with destructive sampling and root studies using minirhizotron techniques. Significantly higher soil CO_2 evolution was observed in the elevated CO_2 treatments in April and October; N effects were not significant. In October, integrated daily values for CO_2 evolution ranged from 3.73 to 15.68 g CO_2 m^{-2} day^{-1} for the ambient CO_2 + 0 N and 525 µL L^{-1} CO_2 + 20 g.m^{-2} N, respectively. Soil CO_2 flux among treatments was correlated with coarse root biomass ($r^2 = 0.40$; $p > F = 0.0380$), indicating that at least some of the variation observed among treatments was related to variation in root respiration. Across all sample periods and treatments, there was a significant correlation ($r^2 = 0.63$; $p > F = 0.0001$) between soil CO_2 evolution and percent fungal hyphae observed in minirhizotron tubes. Hence, some of the seasonal and treatment variation was also related to differences in heterotrophic activity.

Yoshida, Lidia C., John A. Gamon and Christian P. Andersen. 2001. Differences in above- and below-ground responses to ozone between two populations of a perennial grass. Plant and Soil 233:203-211.

Our study examined the influence of elevated ozone levels on the growth and mycorrhizal colonization of two populations of *Elymus glaucus* L. (blue wildrye). We hypothesized that ozone would reduce carbon availability to the plants, particularly below ground, and would affect mycorrhizal colonization. Because of the wide geographic range of *E. glaucus,* two populations of plants were selected from areas of contrasting ozone histories to examine intraspecies variation in response to ozone. Two populations of *E. glaucus* (southern California versus northern California) exposed in a factorial experiment involving ozone, mycorrhizal inoculation with *Glomus intraradices* Schenck and Smith, and plant source population. Ozone had a subtle effect on leaf area and number of tillers but did not affect overall root:shoot ratio in either population. The impact of ozone on above-ground growth characteristics was most pronounced in the southern population that came from a high-ozone environment, while below-ground responses such as reduced arbuscular colonization was most pronounced in the northern population which originated in a low-ozone environment. Further analysis of soil characteristics from the northern population of plants revealed a significant reduction in active soil bacterial biomass and an increase in total fungi per gram dry weight soil, suggesting a possible role for ozone in altering soil processes. Whether or not population differences in response to ozone were due to genetic shifts resulting from prior ozone remains to be determined. However, these subtle but important differences in population response to ozone above- and below-ground have significant implications in any attempt to generalize plant response, even within a species. Future research efforts need to include better characterization of intraspecific variation in response to ozone as well as possible adaptive strategies that may result from chronic ozone exposure.

VEGETATION REDISTRIBUTION

Bugmann, Harald K.M. and Allen M. Solomon. 2000. Explaining forest composition and biomass across multiple biogeographical regions. Ecological Applications 10:95-114.

Current scientific concerns regarding the impacts of global change include the responses of forest composition and biomass to rapid changes in climate, and forest gap models have often been used to address this issue. These models reflect the concept that forest composition and biomass in the absence of large-scale disturbance are explained by competition among species for light and other resources in canopy gaps formed when dominant trees die. Since their initiation 25 yr ago, a wide variety of gap models have been developed that are applicable to different forest ecosystems all over the world. Few gap models, however have proved to be equally valid over a wide range of environmental conditions, a problem on which our work is focused.

We previously developed a gap model that is capable of simulating forest composition and biomass in temperate forests of Europe and eastern North America based on a single model structure. In the present study, we extend the model to simulate individual tree species response to strong moisture seasonality and low temperature seasonality. and we modify the widespread parabolic temperature response function to mimic nonlinear increases in growth with increased temperature up to species-specific optimal values.

The resulting gap model, FORCLIM V2.9. generates realistic projections of tree species composition and biomass across a complex gradient of temperature and moisture in the Pacific Northwest of the United States. The model is evaluated against measured basal area and stand structure data at three elevations of the H. J. Andrews LTER site, yielding satisfactory results. The very, same model also provides improved estimates of species composition and stand biomass in eastern North America and central Europe, where it originated. This suggests that the model modifications we introduced are indeed generic.

Temperate forests other than those we studied here are characterized by climates that are quite similar to the ones in the three study regions. Therefore we are confident that it is possible to explain forest composition and biomass of all major temperate forests by means of a single hypothesis as embodied in a forest gap model.

Cramer, Wolfgang P. and Allen M. Solomon. 1993. Climatic classification and future global redistribution of agricultural land. Climate Research 3:97-110.

Future global carbon (C) cycle dynamics under climates altered by increased concentrations of greenhouse gases (GHGs) will be defined in part by processes which control terrestrial biospheric C stocks and fluxes. Current research and modeling activities which involve terrestrial C have focused on the response of unmanaged vegetation to changing climate and atmospheric chemistry. A common conclusion reached from applying geographically explicit terrestrial carbon models is that more C would be stored by equilibrium vegetation controlled by a stable GHG-warmed climate than by equilibrium vegetation under the current (stable) climate. We examined the potential impact on the terrestrial C cycle if global agriculture were to increase to the limits permitted by future GHG-induced climates. Climatic limits to global agricultural zones were determined, the new climatic limits to agricultural zones projected, and the amount of C the terrestrial biosphere would store under the new climate and agricultural conditions was calculated. We conclude that following a warming loss of C from agriculture could be as important as gain of C by climate effects. As much or less C would be stored by a terrestrial biosphere in which agriculture reached its new climatic limits as is stored by the current biosphere in which agriculture reaches its climatic limits. We project that agriculture alone could produce a C source of 0.3 to 1.7 Pg yr^{-1} if doubling of GHGs required 50 to 100 yr. The gains in agriculture would occur almost entirely in the developed countries of high latitudes, and the losses, in the less developed countries of the lower latitudes.

Droessler, Terry D. In the Footsteps of Robert Marshall: Proposed Research of 'White Spruce Growth and Movement at the Tree Limit, Central Brooks Range, Alaska. Unpublished Manuscript..

The proposed research will quantify white spruce growth and document its latitudinal stability at the tree limit in the central Brooks Range over the life span of the living trees. The, goal is to link tree growth and tree position to summer temperature and precipitation. Historical records from 1929 to 1938 from work by Robert Marshall have been used to identify tree limit sites and provide information to interpret the present location of the tree limit.

King, George A. and Ronald P. Neilson. 1992. The transient response of vegetation to climate change: a potential source of CO_2 to the atmosphere. Water, Air, and Soil Pollution 64:365-383.

Global climate change as currently simulated could result in the broad-scale redistribution of vegetation across the planet. Vegetation change could occur through drought-induced dieback and fire. The direct combustion of vegetation and the decay of dead biomass could result in a release of carbon from the biosphere to the atmosphere over a 50- to 150-year time frame. A simple model that tracks dieback and regrowth of extra-tropical forests is used to estimate the possible magnitude of this carbon pulse to the atmosphere. Depending on the climate scenario and model assumptions, the carbon pulse could range from 0 to 3 Gt of C yr'. The wide range of pulse estimates is a function of uncertainties in the rate of future vegetation change and in the values of key model parameters.

King, George A. and David T. Tingey. 1992. Potential impacts of climate change on Pacific Northwest forest vegetation. US Environmental Protection Agency.

The continued accumulation of radiatively-active trace gases in the atmosphere may significantly alter the climate of the Pacific Northwest. Mean annual temperatures could increase 2° to 5°C. The seasonality of precipitation will likely remain the same, but with annual totals remaining unchanged or increasing 20%.

The potential effects of these climate changes on Northwest forests have been estimated using a variety of modeling approaches and climate scenarios. Overall, 26 to 90% of the area in the Northwest may change from one general vegetation type to another. Forest area in the Northwest could decrease 5 to 25%. Remaining forest land would differ in species composition, and likely be less productive than current forests. In Oregon, drier Douglas-fir dominated forests would increase in area, whereas the more productive western hemlock - Douglas-fir forests would decrease. Forest vegetation zones would rise in elevation from 500 to 1000m. Alpine and subalpine forests could disappear from all but the highest elevations in the region.

Detrital carbon stores in the Oregon Cascades could be reduced by as much as 30% with a 5°C climate warming. Assuming no change in forest productivity, there could be a net loss of 60 Mg of carbon per hectare from the same region. This compares to a decrease in carbon storage of 305-370 Mg per hectare resulting from conversion of old growth forests to young plantations.

Forest disturbances such as fire, wind and pest/pathogen outbreaks will likely increase in frequency, speeding vegetation change in response to climate change. Disturbances imposed on forests through timber management practices may also hasten the response of forests to climate change. Also, current management practices coupled with natural disturbances may inhibit establishment of new forests at the same time as older forests are changing.

There are two key limitations to the data presented here. First, the transient (time-dependent) dynamics of change have not been adequately investigated. How forests respond to a rapidly changing but variable climate is uncertain. Second, the direct effects of enhanced CO_2 concentrations on forest species growth have not been considered in any of the modeling simulations. Laboratory experiments suggest the potential for increased drought tolerance by individual plants under higher CO_2 concentrations. The landscape scale impacts of higher CO_2 concentrations on vegetation and water balance are uncertain.

In sum, natural and human caused disturbances of the landscape will play a major role in the response of regional forests to climate change. The interplay of forest management and natural forest processes needs to be considered in future assessments of climate change impacts on Northwest forests. They also must be considered in designing mitigation options for reducing the impact of climate change on regional forests.

Forest managers are thus presented with a difficult problem. How should current forests be managed given 1) our uncertainty of the magnitude and direction of future climate change and 2) the potential for large changes in forest composition and distribution if the climate does change as currently simulated by state-of-the-art climate models?

Kirilenko, Andrei P. and Allen M. Solomon. 1998. Modeling dynamic vegetation response to rapid climate change using bioclimatic classification. Climatic Change 38:15-49.

Modeling potential global redistribution of terrestrial vegetation frequently is based on bioclimatic classifications which relate static regional vegetation zones (biomes) to a set of static climate parameters. The equilibrium character of the relationships limits our confidence in their application to scenarios of rapidly changing climate. Such assessments could be improved if vegetation migration and succession would be incorporated as response variables in model simulations. We developed the model MOVE (Migration Of VEgetation), to simulate the geographical implications of different rates of plant extirpation and in-migration. We used the model to study the potential impact on terrestrial carbon stocks of climate shifts hypothesized from a doubling of atmospheric greenhouse gas concentration. The model indicates that the terrestrial vegetation and soil could release carbon; the amount of this carbon pulse depends on the rate of migration relative to the rate of climate change. New temperate and boreal biomes, not found on the landscape today, increase rapidly in area during the first 100 years of simulated response to climate change. Their presence for several centuries and their gradual disappearance after the climate ceases to change adds uncertainty in calculating future terrestrial carbon fluxes.

Neilson, Ronald P. 1995. A model for predicting continental-scale vegetation distribution and water balance. Ecological Applications 5:362-385.

A Mapped Atmosphere-Plant-Soil System (MAPSS) has been constructed for simulating the potential biosphere impacts and biosphere-atmosphere feedbacks from climatic change. The system calculates the potential vegetation type and leaf area that could be supported at a site, within the constraints of the abiotic climate. Both woody vegetation and grass are supported and compete for light and water. The woody vegetation can be either trees or shrubs, evergreen or deciduous, and needleleaved or broadleaved. A complete site water balance is calculated and integrates the vegetation leaf area and stomatal conductance in canopy transpiration and soil hydrology. The MAPSS model accurately simulates the distributions of forests, grasslands, and deserts and reproduces observed monthly runoff. The model can be used for predictions of new vegetation distribution patterns, soil moisture, and runoff patterns in alternative climates.

Neilson, Ronald P. 1993. Vegetation redistribution: a possible biosphere source of CO_2 during climatic change. Water, Soil, and Air Pollution 70:659-73.

A new biogeographic model, MAPSS, predicts changes in vegetation leaf area index (LAI), site water balance and runoff, as well as changes in Biome boundaries. Potential scenarios of equilibrium vegetation redistribution under 2 X CO_2 climate from five different General Circulation Models (GCMS) are presented. In general, large spatial shifts in temperate and boreal vegetation are predicted under the different scenarios; while, tropical vegetation boundaries are predicted (with one exception) to experience minor distribution contractions. Maps of predicted changes in forest LAI imply drought-induced losses of biomass over most forested regions, even in the tropics. Regional patterns of forest decline and dieback are surprisingly consistent among the five GCM scenarios, given the general lack- of consistency in predicted changes in regional precipitation patterns. Two factors contribute to the consistency among the GCMs of the regional ecological impacts of climatic change: 1) regional, temperature-induced increases in potential evapotranspiration (PET) tend to more than offset regional increases in precipitation; and, 2) the unchanging background interplay between the general circulation and the continental margins and mountain ranges produces a fairly stable pattern of regionally specific sensitivity to climatic change. Two areas exhibiting among the greatest sensitivity to drought-induced forest decline are eastern North America and eastern Europe to western Russia. Drought-induced vegetation decline (losses of LAI), predicted under all GCM scenarios, will release CO_2 to the atmosphere; while, expansion of forests at high latitudes will sequester CO_2. The imbalance in these two rate processes could produce a large, transient pulse of CO_2 to the atmosphere.

Neilson, Ronald P., George A. King, Robert L. DeVelice and James M. Lenihan. 1992. Regional and local vegetation patterns: the responses of vegetation diversity to subcontinental air masses *in* Landscape Boundaries. Hansen, A.J. and F. Di Castri, editors. Pp 129-149.

The prospect of global change, fostered by human impacts on the global climate and by extensive alteration of the natural landscape, has raised concerns over the fate of the earth's natural biological diversity. Unfortunately, a definitive theory on the causes of biological diversity has been elusive. The absence of such a theory makes it difficult to project the consequences of global change on biodiversity. The ideal theory of biodiversity must, at least, be able to explain the spatial patterns of biodiversity and their changes through time. Our intent, in this chapter, is to explore some of the spatial patterns of biodiversity and to propose a few mechanisms that appear to account for much of this pattern. We are particularly attentive to the potential climatic drivers of spatial patterns of biodiversity.

Diversity can be defined in many different ways. Two manifestations of diversity are addressed in this chapter: (1) diversity of form (i.e., physiognomy), and (2) diversity of species. *Physiognomy* is used here to refer to both the plant life forms that are used to characterize biomes (Beard 1978) and to vegetation structure within a biome (e.g., the different relative amounts of overstory and understory life forms). Species diversity has two components: richness and evenness (Whittaker 1972, Cody 1975). *Species richness* is the number of species in a sample, while *evenness* refers to their relative abundances (Whittaker 1972, Cody 1975). We restrict our discussion to species richness.

Spatial patterns of both physiognomic and species diversity have resulted from processes on two vastly different time scales: evolutionary and ecological. Over evolutionary time, new species and life forms arise, but this process usually requires millennia for terrestrial plants. Over ecological time, from years to centuries, evolution can be assumed to be static, and spatial patterns of species diversity arise from different spatial arrangements of species due to climatic and substrate forcing or to ecological interactions. Evolutionary time frames and processes are not discussed in this chapter. Rather, we attempt to extract the different influences of climate over short time scales on spatial patterns of diversity across a range of spatial scales. In addition to the separation of potential causes of diversity patterns at different scales, we look for mechanistic relationships between climate at large spatial scales and patterns of diversity at large and small spatial scales.

Recent reports suggest that climatic change could cause biomes to shift several hundred kilometers across the earth and that the physiognomy of any given biome could rapidly change to something quite different (e.g., Solomon 1986, Neilson et al. 1989, Winjum and Neilson 1989, Neilson et al. 1990). Both types of change-spatial and physiognomic-could threaten the extinction of large numbers of species. The ecotones between major biomes are probably landscapes that are sensitive to climatic change (di Castri et al. 1988) and should possess patterns of biodiversity that are unique relative to more central biome areas. We first describe a theory of physiognomic diversity and spatial distribution as driven by large-scale climatic patterns. This theory should explain the general physiognomy within biomes, as well as the location of the ecotones between biomes. We then attempt to relate local patterns of species diversity to the distributions of biomes, with particular attention to the relationships between diversity patterns and ecotones at regional and local scales.

Neilson, Ronald P., George A. King and Greg Koerper. 1992. Toward a rule-based biome model. Landscape Ecology 7:27-43.

Current projections of the response of the biosphere to global climatic change indicate as much as 50% to 90% spatial displacement of extratropical biomes. The mechanism of spatial shift could be dominated by either 1) competitive displacement of northern biomes by southern biomes, or 2) drought-induced dieback of areas susceptible to change. The current suite of global biosphere models cannot distinguish between these two processes, thus determining the need for a mechanistically based biome model. The first steps have been taken towards the development of a rule-based, mechanistic model of regional biomes at a continental scale. The computer model is based on a suite of empirically generated conceptual models of biome distribution. With a few exceptions the conceptual models are based on the regional water balance and the potential supply of water to vegetation from two different soil layers, surface for grasses and deep for woody vegetation. The seasonality of precipitation largely determines the amount and timing of recharge of each of these soil layers and thus, the potential mixture of vegetative life-forms that could be supported under a specific climate. The current configuration of rules accounts for the potential natural vegetation at about 94% of 1211 climate stations over the conterminous U.S. Increased temperatures, due to global warming, would 1) reduce the supply of soil moisture over much of the U.S. by reducing the volume of snow and increasing winter runoff, and 2) increase the potential evapotranspiration (PET). These processes combined would likely produce widespread drought-induced dieback in the nation's biomes. The model is in an early stage of development and will require several enhancements, including explicit simulation of PET, extension to boreal and tropical biomes, a shift from steady-state to transient dynamics, and validation on other continents.

Neilson, Ronald P. 1993. Transient ecotone response to climatic change: some conceptual and modelling approaches. Ecological Applications 3:385-395.

Accurate prediction of the ecological impacts of climatic change is a pressing challenge to the science of ecology. The cur-rent state of the art for broad-scale estimates of change in biomes and ecotones between biomes is limited to equilibrium estimates of ecological change under some future equilibrium climate. Uncertainties in these estimates abound, ranging from uncertainties in future climate scenarios to uncertainties in our ecological models and finally to uncertainties in modelling the feedbacks between the climate and the biosphere. Ecologists and policymakers need to go beyond equilibrium estimates of biosphere change to transient responses of the biosphere as the climate changes. Ecotones between biomes have been suggested as sensitive areas of change that could be effectively modelled and monitored for future change. Ecotones are also important in influencing local and regional biodiversity patterns and ecological flows. The ecological processes that could affect change at ecotones and within biomes are discussed; they include internal ecosystem processes, such as competition, and external abiotic processes, most notably drought and related disturbances. Drought followed by infestations and fire appears to be the most likely process that could mediate ecological change under a rapidly changing climate. The impacts would be apparent all across biomes, not just at ecotones. However, specific predictions about the dynamics of ecotones can be made qualitatively, based on a theory of patch scaling and diversity in relation to abiotic stressors. Under current conditions, the size of homogeneous patches is expected to be small at ecotones, but to enlarge with distance from the ecotone. Directional climatic change should promote a coalescence of patches on one side of the ecotone and increased fragmentation on the other side. Ecotones should begin to blur as viewed from a satellite only to re-form at some later date in a new location. This view is in contrast to the notion that ecotones would retain sharp distinction and simply move across the landscape. These changes are presented as hypotheses based on theory and should be testable in a mechanistic modeling framework that is only now being developed.

Nielson, R.P., L.F. Pitelka, A.M. Solomon, R. Nathan, G. F. Midgley, J.M.V. Fragoso, H. Lischke, and K. Thompson. 2005. Forecasting regional to global plant migration in response to climate change. Bioscience 55 (9): 749-759.

The rate of future climate change is likely to exceed the migration rates of most plant species. The replacement of dominant species by locally rare species may require decades, and extinctions may occur when plant species cannot migrate fast enough to escape the consequences of climate change. Such lags may impair ecosystem services, such as carbon sequestration and clean water production. Thus, to assess global change, simulation of plant migration and local vegetation change by dynamic global vegetation models (DGVMs) is critical, yet fraught with challenges. Global vegetation models cannot simulate all species, necessitating their aggregation into plant functional types (PFTs). Yet most PFTs encompass the full spectrum of migration rates.Migration processes span scales of time and space far beyond what can be confidently simulated in DGVMs. Theories about climate change and migration are limited by inadequate data for key processes at short and long time scales and at small and large spatial scales. These theories must be enhanced to incorporate species-level migration and succession processes into a more comprehensive definition of PFTs.

Solomon, Allen M. and Patrick J. Bartlein. 1992. Past and future climate change: response by mixed deciduous-coniferous forest ecosystems in northern Michigan. Canadian Journal of Forest Research 22:1727-1738.

During the 21st century, global climate change is expected to become a significant force redefining global biospheric boundaries and vegetation dynamics. In the northern hardwood - boreal forest transition forests, it should, at the least, control reproductive success and failure among unmanaged mixed forest stands. One means by which to predict future responses by the mixed forests is to examine the way in which they have responded to climate changes in the past. We used proxy climate data derived from Holocene (past 10 000 years) pollen records in the western Upper Peninsula of Michigan to drive forest gap models, in an effort to define regional prehistoric vegetation dynamics on differing soils. The gap models mimic forest reproduction and growth as a successional process and, hence, are appropriate for defining long-term tree and stand dynamics. The modeled period included a mid-postglacial period that was warmer than today's climate. Model failures, made apparent from the exercise, were corrected and the simulations were repeated until the model behaved credibly. Then, the same gap model was used to simulate potential future vegetation dynamics, driven by projections of a future climate that was controlled by greenhouse gases. This provided us with the same "measure" of vegetation in the past, present, and future, generating a continuously comparable record of change and stability in forest composition and density. The resulting projections of vegetation response to climate change appear to be affected more by the rate than by the magnitude of climate change.

Solomon, Allen M. 1997. Natural migration rates of trees: Global terrestrial carbon cycle implications *in* Past and Future Rapid Environmental Changes: The Spatial and evolutionary Responses of Terrestrial Biota. Brian Huntley et al., editors. NATO ASI Series, Vol. 147. Pp.455-468

Migration of populations or species of trees ('tree migration') in response to climate change is of interest both to palaeoecologists who assess past vegetational as responses to climate change, and to global ecologists concerned with future climate change induced by increasing greenhouse gases (GHGs). A major difference between climate-driven tree migrations in prehistory and those expected in the future is the high speed of the latter climate change. The 4-6 km which temperate-zone July isotherms are predicted to move northward annually (Solomon et al. 1984) are about an order of magnitude more rapid than prehistoric rates deduced from palaeoecological evidence. Assuming prehistoric rates of warming matched the rate of tree migration (T Webb 1986; Prentice et al. 1991), fossil pollen data allow inference of 400 m yr' (Davis 1983) to 800 m yr^1 (Gear & Huntley 1991) of climate change and tree migration at most. The rate may be even slower if tree migration includes the establishment and maturity of the tree population (Bennett 1986) as well as the processes of seed transport, establishment, growth and seed production, normally defined as migration (e.g. Davis 1989; MacDonald et al. 1993).

The difference in definition is important for predicting the amount of carbon (CO_2 is the most important of the GHGs) that will reside in the atmosphere in the future. The oceans provide the ultimate long-term control on atmospheric carbon concentrations (e.g. Sundquist 1985; Prentice et al. 1993). However, the terrestrial biosphere modulates the shorter-term changes in carbon content, measured over a few decades or centuries (Gammon et al. 1985; Keeling et al. 1995; Denning et al. 1995). Forests store about 2/3 of above-ground terrestrial organic carbon and over half of the carbon present in the world's soils (Dixon et al. 1994). The presence of a few trees on the landscape (e.g. MacDonald et al. 1993), indicated by establishment and reproductive maturity of seed trees, contributes little carbon to terrestrial stocks. Instead, closed-canopy stands of mature mixed or pure species provide the dense carbon stocks of interest. These are associated with mature, stable populations.

Projections of global terrestrial carbon cycle dynamics under warmer climates of a doubled GHG concentration have used static vegetation models (Prentice & Solomon 1990). These projections hinge on the critical assumption that the migration of trees and the formation of mature, stable populations at new locations proceeds at the same rate as the climate change to which it is responding (Sedjo & Solomon 1989; Leemans 1989; Prentice & Fung 1990; Smith et al. 1992a, b; Smith & Shugart 1993a, b; Solomon et al. 1993). To date, these static model exercises have projected increased global terrestrial carbon storage under future warming, because large new land areas suitable for forest growth are created either by warming of high latitude treeless tundra, or by increased hydrologic cycle intensity in treeless steppe.

Yet, unchanged or decreased rather than increased carbon storage may result if forests cannot migrate and establish in the time required to attain the doubled GHG benchmark. The objective of the current paper is to estimate the time required for forests to develop in regions new to them, to estimate the time required for forests to die out where they become climatically obsolete, then to calculate the impacts of those times on future terrestrial carbon stocks.

Solomon, Allen M. and Darrell C. West. 1993. Predicting afforestation success during climatic warming at the northern limit of forests *in* Forest Development in Cold Climates. J. Alden et al., editors. Pp. 167-188.

Global temperature increases from greenhouse gases are expected during the 21st Century, possibly as early as the next decade. Warming is predicted to be greatest at highest latitudes. Initial attempts to document climate change will be hampered by the great inter-annual variability in weather at high latitudes and the scarcity of long-term weather records. Certain key properties of these environmental changes, however, can be defined, despite uncertainty concerning results from present climate models. A group of scientists meeting at Villach, Austria, in 1987 (Jaeger, 1988) agreed that 3 °C was a moderate estimate of average global warming during the next century, while at high latitudes (60 to 90° N.), 0.6 to 0.7 °C per decade in winter and 0.1 to 0.2 °C per decade in summer are more probable climate change expectations. Results from the most recent climate model results are not very different and range from 0.4 to 0.8 °C per decade (Mitchell et al., 1990). In addition, results from both the Villach group and the more recent compilations agree that winter precipitation and soil moisture could increase at high latitudes as more precipitation falls, and as more precipitation falls as rain instead of snow. These climate changes are quite intense and rapid. For the next few decades, they may result in a much wider range of temperature and precipitation extremes than has ever been recorded in cold regions.

WATER RESOURCES

Dolph, Jayne, Danny marks and George A. King. 1992. Sensitivity of the regional water balance in the Columbia River Basin to climate variability: application of a spatially distributed water balance model. *In* New Perspectives for Watershed Management: Balancing Long-term Sustainability with Cumulative Environmental Change; R.J. Naiman and J.R. Sedell, editors. Pp 233-265.

A one-dimensional water balance model was developed and used to simulate the water balance for the Columbia River Basin. The model was run over a 10 km digital elevation grid representing the U.S. portion of the basin. The regional water balance was calculated using a monthly time step for a relatively wet year (1972 water year), a relatively dry year (1977 water year), and a double ($2xCO_2$) climate scenario. Input data, spatially distributed over the grid, included precipitation, maximum soil moisture storage capacity, potential evapotranspiration (PET), and threshold baseflow. The model output provides spatially distributed surfaces of actual evapotranspiration (ET), runoff, and soil storage. Model performance was assessed by comparing modeled ET and runoff with the input precipitation data, and by comparing modeled runoff with measured runoff. The model reasonably partitions incoming precipitation to evapotranspiration and runoff. However, modeled total annual runoff was significantly less than measured runoff, primarily because precipitation is underestimated by the network of measurement stations and because of limitations associated with the interpolation procedure used to distribute the precipitation across the grid. Estimated precipitation is less than measured runoff, a physical impossibility. Under warmer $2xCO_2$ climate conditions (January 4.0°K warmer, July 6.5°K warmer), the model predicts that PET increases by about 80%, ET increases, and runoff and soil moisture decrease. Under these climate conditions, the distribution and composition of forests in the region would change dramatically, and water resources would become more limited.

Lettenmaier, Dennis P., Kenneth L. Brettmann, Lance W. Vail, Steven B. Yabusaki and Michael J. Scott. 1992. Sensitivity of Pacific Northwest water resources to global warming. The Northwest Environmental Journal 8:265-283.

The potential effect of increasing atmospheric concentrations of carbon dioxide and other so-called greenhouse gases on the land surface environment is not well understood. Generally, there is some consistency among computer models of global climate that surface temperatures will increase and that, in many areas, precipitation and evaporation also may increase. However, determining the effects of such changes on the distribution and circulation of water at the land surface, and on water management systems, remains problematic. The American River, Washington, a mountainous tributary of the Yakima River, is typical of rivers in the Columbia Basin states of Washington, Oregon, Idaho, and western Montana, as well as southern British Columbia. Using the American River as a case study, this investigation developed computer models to simulate and identify water management conflicts that might arise in this region under a general climate warming of both 2° C and 4° C. For warmer climates, it was found that snow accumulation would be substantially reduced, and the river's high flow season would shift from the spring to the winter. Potential evaporation would increase throughout the year (mostly in the summer), but peak actual evaporation would shift to the late spring and early summer, due to reduced summer soil moisture. The effect of the streamflow pattern that would accompany a warmer climate was tested on small and moderate sized hypothetical multi-purpose reservoirs. The results showed that water supply reliability would be significantly degraded by the earlier spring runoff pattern that would accompany a warmer climate, especially for small reservoirs. The result was that hydroelectric revenues might increase due to larger reservoir releases needed during the winter peak demand season. An investigation of alternative operating policies for the reservoir system showed that more efficient reservoir operation alone would not mitigate the degraded reliability of water supply that would accompany a warmer climate.

Lettenmaier, Dennis P. and Thian Yew Gan. 1990. Hydrologic sensitivities of the Sacramento-San Joaquin River Basin, California, to global warming. Water Resources Research 26:69-86.

The hydrologic sensitivities of four medium-sized Mountainous catchments in the Sacramento and San Joaquin River basins to long-term global warming were analyzed. The hydrologic response of these catchments, all of which are dominated by spring snowmelt runoff, were simulated by the coupling of the snowmelt and the soil moisture accounting models of the U.S. National Weather Service River Forecast System. In all four catchments the global warming pattern, which was indexed to CO_2 doubling scenarios simulated by three (global) general circulation models, produced a major seasonal shift in the snow accumulation pattern. Under the alternative climate scenarios more winter precipitation fell as rain instead of snow, and winter runoff increased while spring snowmelt runoff decreased. In addition. large increases in the annual flood maxima were simulated, primarily due to an increase in rain-on-snow events, with the time of occurrence of many large floods shifting from spring to winter.

Lettenmaier, Dennis P. and Daniel P. Sheer. 1991. Climatic sensitivity of California water resources. Journal of Water Resources Planning & Management 117:108-125.

The possible effects of climate change on the combined Central Valley Project-California State Water Project (CVP/SWP) were evaluated using a three-stage approach. In the first stage, runoff from four headwater “study catchments” was simulated using rainfall/snowmelt-runoff models, with climatic input taken from CO_2 doubling scenarios from three general circulation models (GCMs). In the second stage, long-term inflows to the CVP/SWP reservoir system were simulated, conditioned on the study catchment flows, using a stochastic disaggregation model. In the third stage, a system simulation model was used to evaluate performance of the reservoir system. For all of the alternative climate scenarios, runoff would be shifted from the spring to the winter. Significantly lower water deliveries from the SWP would occur under the CO_2 doubling scenarios. The reduced deliveries would occur because some of the increased winter runoff would be spilled from the reservoirs instead of being stored in the snowpack, even though the mean annual runoff increased slightly under some climate scenarios. Annual San Francisco Bay delta flows would increase under all three climate scenarios; however, flows to the bay would be substantially increased in winter and somewhat decreased in spring and summer.

Marks, Danny, John Kimball, Dave Tingey, and Tim Link. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a study of the 1996 Pacific Northwest flood. Hydrological Processes 12:1569-1587.

A warm, very wet Pacific storm caused major flooding in the Pacific Northwest during February 1996. Rapid melting of the mountain snow cover contributed to this flooding. An energy balance snow melt model is used to simulate snow melt processes during this event in the Central Cascade mountains of Oregon. Data from paired open and forested experimental sites at locations at and just below the Pacific Crest were used to drive the model. The event was preceded by cold, stormy conditions that developed a significant snow cover down to elevations as low as 500m in the Oregon Cascades. At the start of the storm, the depth of the snow cover at the high site (1142 m) was 1·97m with snow water equivalent (SWE) of 425 mm, while at the mid site (968 m) the snow cover was 1·14 with SWE of 264 mm. During the 5-6 day period of the storm the high site received 349 mm of rain, lost 291 mm of SWE, and generated 640 mm of runoff, leaving only 0.22 m of snow on the ground. The mid site received 410 mm of rain, lost 264 mm of water to melt, and generated 674 mm of runoff, completely depleting the snow cover. Simulations at adjacent forested sites showed significantly less snow melt during the event. The snow cover under the mature forest at the high site lost only 44 mm of SWE during the event, generating 396 mm of runoff, and leaving 0.69 m of snow. The model accurately simulated both depth and SWE during the development of the snow cover prior to the storm, and the depletion of the snow cover during the event. This analysis shows that because of the high temperature, humidity, and relatively high winds in the open sites during the storm, 60-90% of the energy for snow melt came from sensible and latent heat exchanges. Because the antecedent conditions extended the snow cover to very low elevations in the basin, snow melt generated by condensation during the event made a significant contribution to the flood. Lower wind speeds beneath the canopy during the storm reduced the magnitude of the turbulent exchanges at the snow surface, so the contribution of snow melt to the runoff from forested areas was significantly less. This experiment shows the sensitivity of snow melt processes to both climate and land-cover, and illustrates how canopy structure is coupled to the hydrologic cycle in mountainous areas.

Marks, Danny, George A. King and Jayne Dolph. 1993. Implications of climate change for the water balance of the Columbia River Basin, USA. Climate Research 2:203-213.

Global climate change will affect the terrestrial biosphere primarily through changes i n regional energy and water balance. Changes in soil moisture and evapotranspiration will particularly affect water and forest resources. Existing spatially lumped hydrologic models are not adequate to analyze the potential effects of climate change on the regional water balance over large river basins or regions primarily because they do not satisfactorily account for the spatial and temporal variability of hydrologic processes. Here we summarize application of a spatially distributed water balance model that was tested using historical data from the U.S. portion of the Columbia River Basin in the Pacific Northwest for a very dry (1977) and very wet (1972) water year. The model adequately partitions incoming precipitation into evapotranspiration and runoff. Because precipitation in the basin is underestimated from measured data, modeled runoff is less than measured runoff from the basin during both the wet and dry years. The potential effects of climate change on runoff and soil moisture in the Columbia River Basin were simulated using 2xCO_2 scenario data from the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation model (GCM). The predicted future climate conditions significantly increase potential evapotranspiration, causing a 20% reduction in runoff relative to input precipitation, and a 58 % reduction in soil moisture storage. If these changes in regional water balance are realized, the distribution and composition of forests in the Northwest would change markedly, and water resources would become more limited. Because of uncertainties in future climate scenarios, and limitations in the implementation of the water balance model, the 2 x CO_2 results should be viewed only as a sensitivity analysis.

Neilson, Ronald P. and Danny Marks. 1994. A global perspective of regional vegetation and hydrologic sensitivities from climatic change. Journal of Vegetation Science 5:715-730.

A biogeographic model, MAPSS (Mapped Atmosphere-Plant-Soil System), predicts changes in vegetation leaf area index (LAI), site water balance and runoff, as well as changes in biome boundaries. Potential scenarios of global and regional equilibrium changes in LAI and terrestrial water balance under 2 X CO_2 climate from five different general circulation models (GCMS) are presented. Regional patterns of vegetation change and annual runoff are surprisingly consistent among the five GCM scenarios, given the general lack of consistency in predicted changes in regional precipitation patterns. Two factors contribute to the consistency among the GCMs of the regional ecological impacts of climatic change: (1) regional, temperature-induced increases in potential evapotranspiration (PET) tend to more than offset regional increases in precipitation; and (2) the interplay between the general circulation and the continental margins and mountain ranges produces a fairly stable pattern of regionally specific sensitivity to climatic change. Two areas exhibiting among the greatest sensitivity to drought-induced forest decline are eastern North America and eastern

Europe to western Russia. Regional runoff patterns exhibit much greater spatial variation in the sign of the response than do the LAI changes, even though they are deterministically linked in the model. Uncertainties with respect to PET or vegetation water use efficiency calculations can alter the simulated sign of regional responses, but the relative responses of adjacent regions appear to be largely a function of the background climate, rather than the vagaries of the GCMS, and are intrinsic to the landscape. Thus, spatial uncertainty maps can be drawn even under the current generation of GCMS.