DOI: 10.1007/s00267-003-9103-8

Monitoring Forest Carbon Sequestration with Remote Sensing and Carbon Cycle Modeling

DAVID P. TURNER*
MICHAEL GUZY
Department of Forest Science
Oregon State University
Corvallis, Oregon 97331-5752, USA

MICHAEL A. LEFSKY
Department of Forest Sciences
Colorado State University
Ft. Collins, Colorado 80523-1470, USA

WILLIAM D. RITTS
STEVE VAN TUYL
BEVERLY E. LAW
Department of Forest Science
Oregon State University
Corvallis, Oregon 97331-5752, USA

ABSTRACT / Sources and sinks of carbon associated with forests depend strongly on the management regime and spatial patterns in potential productivity. Satellite remote sensing can provide spatially explicit information on land cover, stand-age class, and harvesting. Carbon-cycle process models coupled to regional climate databases can provide information on potential rates of production and related rates of decomposition. The integration of remote sensing and modeling thus produces spatially explicit information on carbon storage and flux. This integrated approach was employed to compare carbon flux for the period 1992–1997 over two 165-km^2 areas in western Oregon. The Coast Range study area was predominately private land managed for timber production, whereas the West Cascades study area was predominantly public land that was less productive but experienced little harvesting in the 1990s. In the Coast Range area, 17% of the land base was harvested between 1991 and 2000. Much of the area was in relatively young, productive-age classes that simulations indicate are a carbon sink. Mean annual harvest removals from the Coast Range were greater than mean annual net ecosystem production. On the West Cascades study area, a relatively small proportion ($< 1\%$) of the land was harvested and the area as a whole was accumulating carbon. The spatially and temporally explicit nature of this approach permits identification of mechanisms underlying land base carbon flux.

Forests are large reservoirs of carbon as well as potential carbon sinks and sources to the atmosphere. In temperate North America, forest carbon sinks are believed to offset a significant proportion of carbon emissions associated with fossil fuel combustion (Bosquet and others 2000). In the United States, forest carbon sinks have been estimated to offset up to 24% of the fossil fuel source (USDA Forest Service 2001). Thus, the ability to monitor forest carbon sequestration is of great interest in relation to understanding the current status of the global carbon cycle and to meeting requirements in the United Nations Framework Convention on Climate Change to quantify carbon sources and sinks associated with land use (UN FCCC 1992; Parson and others 1992).

Analysis of forest inventory data provides a capability for monitoring wood production and carbon sequestration (e.g., Birdsey and others 1993). A land-base carbon flux estimate derived from forest inventory data is usually estimated as the difference between volumes measured at two points in time. However, these estimates are often poorly resolved spatially (regions) and temporally (5–10 years), and the mechanisms that account for spatial and temporal patterns are poorly understood. An alternative approach to evaluating forest carbon pools and flux and assessing potential responses to climate change is the application of ecosystem carbon-cycle models in a spatially distributed mode (Schimel and Potter 1995).

For the study of contemporary carbon flux, a carbon-cycle model is initialized with high-spatial-resolution (30 m) satellite remote sensing of surface vegetation characteristics and driven with spatially derived climate from distributed meteorological stations (e.g., Kimball and others 1997; Turner and others 2003). The result is an estimate of net ecosystem production (NEP) for each grid cell. NEP is the net effect of photosynthetic carbon uptake and release of carbon to the atmosphere from respiration by autotrophs (plants) and heterotrophs. It can also be calculated as the difference between net primary production (NPP) and heterotro-

KEY WORDS: Carbon; Forest; Monitoring; Remote sensing; Modeling

Published online March 4, 2004.

*Author to whom correspondence should be addressed, *email:* david.turner@oregonstate.edu

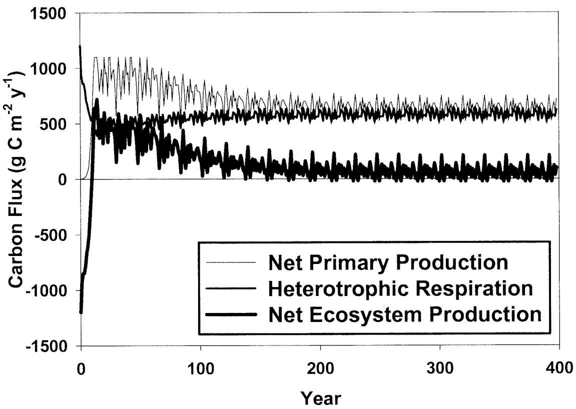


Figure 1. The trends in net primary production, heterotrophic respiration, and net ecosystem production over the course of succession. Values are from a simulation with the Biome-BGC model at a mid-elevation site in the Coast Range. The climate data are repeating loops of an 18-year daily climatology.

phic respiration. Repeated remote sensing coverage of the land area over intervals of several years permits the identification of areas with stand replacing disturbances (harvesting or burning), which provides complimentary information on carbon transfers off the land base.

In this study, the integration of remote sensing and modeling was used to monitor forest carbon sequestration in two 165-km^2 areas in the Pacific Northwest. The objective was to compare carbon flux in two forested areas differing in management history and productive potential.

Methods

The NEP scaling methods and initial validation results for their application in the Pacific Northwest have been reported previously (Turner and others 2003; Law and others in press) and are briefly reviewed here. The primary scaling tool in this approach is the Biome-BGC carbon-cycle process model (Law and others 2001; Thornton and others 2002). The model has a daily time step and is run over multiple years to simulate primary and secondary succession. Simulated processes include photosynthesis, plant respiration, heterotrophic respiration, plant carbon allocation, and plant mortality. In the simulations, NEP is negative right after harvest, strongly positive in early succession to mid-succession, and remains level or declines to near zero in late succession (Figure 1). This general pattern has been observed in a variety of chronosequence studies (Sprugel 1985; Law and others 2001).

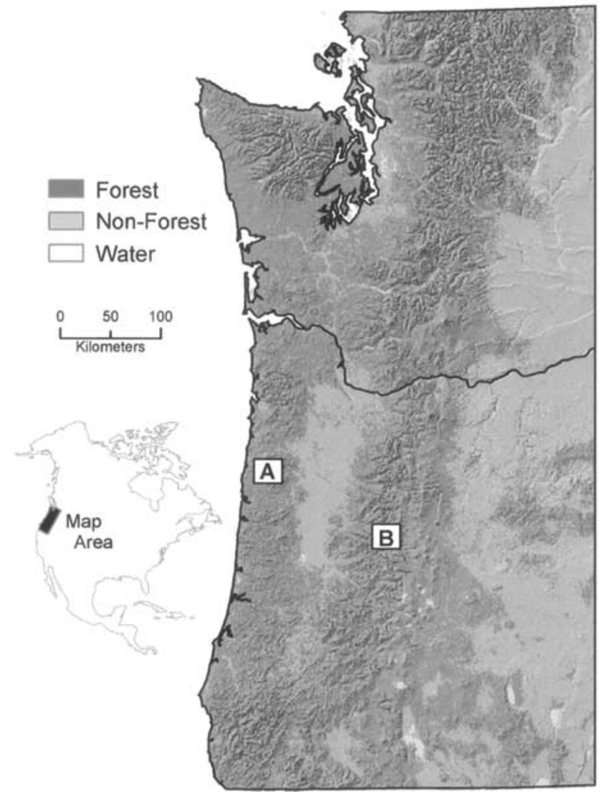


Figure 2. The Pacific Northwest region. The studies areas are in the Coast Range (A) and the West Cascades Mountains (B).

For this study, Biome-BGC was run over a 25-m resolution grid for two areas of interest in western Oregon. Much of the forested portion of the Pacific Northwest is characterized by patches smaller than 1 km^2 that originated from clearcut harvesting (Cohen and others 1998), and stand age is a strong determinant of carbon flux (Sprugel 1985; Law and others in press). Thus, a 25-m resolution is essential to characterize spatial patterns in carbon flux (Cohen and others 1996; Turner and others 2000).

Two areas (each 165 km^2) were selected (Figure 2) to provide a contrast in productivity and land use. The Coast Range study area is at relatively low elevations (mean of 383 m), has high soil nitrogen and potential productivity, and is intensively managed for wood production. The West Cascades area is at higher elevations (mean of 902 m) with colder winter temperatures, more snow, and seasonally dry summers. The West Cascades study area is largely public land that, for the most part, has not been harvested in the last 10 years.

The requirements for model initialization include specification of land-cover type (e.g., conifer versus deciduous forest) and a stand age. Land cover determines the set of ecophysiological constants used in the

Table 1. Land areas by cover type in the study areas

Cover type	Coast range (km^2)	West Cascades (km^2)
Conifer		
Regeneration (1–13)	29.7	2.5
Regeneration (14–29)	7.9	7.9
Young (30–99)	45.3	22.4
Mature (100–200)	3.7	36.5
Old (+200)	0.8	33.9
Broadleaf	22.8	3.9
Mixed	45.9	37.6
Semiopen	6.6	17.9
Open	2.2	1.7
Other	0.1	0.7
Total	165.0	165.0

Note: Ranges for stand age are given for conifer classes.

model (the EPC file), and stand age determines the age to which the model simulation is run after a stand-initiating disturbance to estimate current carbon pools and flux. The land-cover analysis resolved five primary vegetation classes (Table 1). The conifer, broadleaf, and mixed classes were all > 85% cover, whereas the semiopen class was 31–84% cover and the open class was < 30% cover. EPC files were created for each cover type based on White and others (2000) and recent field measurements (Law and others in press).

For all stands < 30 years of age, the year of stand origin was determined from remote sensing. These estimates were provided by analysis of current imagery from the Landsat Thematic Mapper+ sensor and change detection analysis using additional Landsat Thematic Mapper and Multispectral Scanner imagery from the last 30 years (Cohen and others 1995, 2002). These stands were aggregated into two classes: those 1–13 and those 14–29. For conifer stands > 29 years, the remote sensing analysis was able to resolve three classes; young (30–99), mature (100–200), and old (> 200). For the other cover types, a reference age of 45 years was used that reflected the limited knowledge that they were > 29 years old based on the change detection analysis.

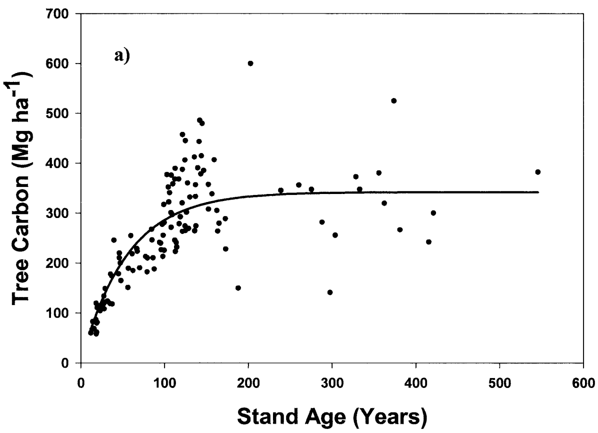
To drive the model, a daily climatology of minimum temperature, maximum temperature, precipitation, humidity, and solar radiation is needed. That data were provided by the DAYMET model, which performs spatial interpolation between meteorological stations using a Digital Elevation Model (DEM) and general climatological principles such as lapse rates (Thornton and others 1997; Thornton and Running 1999; Thornton and others 2000). DAYMET was run over a 1-km grid for the conterminous United States and the climate database covered the 18 years from 1980 to 1997 (courtesy of P. Thornton, National Center for Atmospheric Research).

The Biome-BGC model is sensitive to the leaf area index (LAI), which may also be derived from remote sensing (Spanner and others 1994; Turner and others 1999). However, the LAI cannot by directly prescribed because it is self-regulating within the model. The relatively dry summers in the Pacific Northwest mean that the water storage capacity associated with soil depth strongly influences the maximum LAI that can be supported on a site (Grier and Running 1977). Therefore, an initial set of model runs was made for each cover class within each 1-km grid cell using different soil depths to determine the soil depth that resulted in an LAI closely matching the corresponding LAI from remote sensing. Note that soil depth also impacts NPP and, hence, pools of aboveground and belowground carbon, so uncertainties in the remote-sensing-based LAI (Law and others in press) tend to be propagated into the carbon flux estimates.

Once the input datasets were assembled, a model “spin-up” was conducted for 1000+ years to generate the slow turnover soil carbon pools and bring them into near-steady-state. The magnitude of the soil carbon pools is important because these pools continue to support heterotrophic respiration after a disturbance and, thus, must be correctly estimated to accurately simulate NEP in early succession. For the spin-up, the 18-year climate record was repeated as needed. To account for the effects of wood residues from previous disturbances on NEP, a disturbance regime was imposed in the model runs after the spin-up such that two clearcut harvests preceded the final secondary succession. In these disturbances, a specified proportion of tree carbon (70%) was transferred off site and the remainder was assumed to stay on site to decompose.

After the spin-up and the disturbances, the model was run forward to the age associated with the remote sensing classification. For the conifer cover type, the reference age was the midpoint of the age range for the remote-sensing-based classes. In the model runs, yearly meteorological files were arranged as needed such that for all runs, the last 18 years were 1980–1997. Outputs were saved as surfaces for each year from 1980 to 1997 and included NPP, stemwood production, NEP, and live carbon mass. The resulting map of NEP accounted for all biologically driven carbon fluxes. A mean value for the last 5 years of the simulation was used in reporting the results to minimize effects of interannual variation in climate.

Carbon is also transferred off the land base by harvesting and fire. To account for harvests, a flux was estimated based on the change detection analysis (Co-



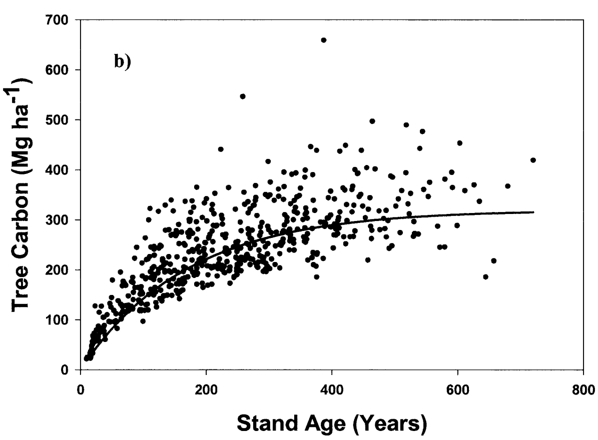


Figure 3. The relationship of aboveground wood carbon to stand age for (a) the Coast Range ecoregion and (b) the West Cascades ecoregion. The data are from Law and others (in press) and represent the highest one third of plots from the USDA Forest Service Current Vegetation Survey plots in each ecoregion. The lines are least-squares fits to the Chapman–Richards function (Richards 1959).

hen and others 2002). Surfaces for land cover in 2000 and 1991 were compared and all forested area that had been harvested was identified. The amount of aboveground tree carbon at the time of harvest was based on an ecoregion-specific relationship of stand age to aboveground tree carbon (Figure 3). A stand age of 90 was assumed (Spies and others 1994). After adding an estimate of carbon in coarse roots to the aboveground tree carbon estimate, the proportion of tree carbon removed from the land base at harvest was derived from the relationship of merchantable to total tree carbon in Turner and others (1995). Burned areas should be treated differently because a larger proportion of tree carbon is usually left after disturbance, but fire was not a significant factor in these areas during the study period.

Results and Discussion

Land-Cover and Stand-Age Class Distribution

The land cover in both study areas was predominantly conifer forest (Figure 4, Table 1). In the more mesic Coast Range, red alder (*Alnus rubra*) competes with conifer species across much of the landscape, resulting in a relatively large proportion of the area as mixed conifer/hardwood (21%) or hardwood (11%). Overall accuracy of the remote sensing classification for a large area in western Oregon was on the order of 80% based on validation with aerial photography (Cohen and others 1995, Law and others in press).

The stand-age class distribution within the conifer class was dominated by relatively young stands in the Coast Range study area but relatively old stands in the West Cascades area (Table 1). Less than 4% of the Coast Range area was classified as mature or old conifer compared with 21% in the West Cascades area. Much of the Coast Range was heavily logged or burned in the early part of the 20th century, leaving little area in the oldest age classes. The area continues to be logged with a dispersed clearcutting approach (Figure 4). The cutting in the West Cascades was largely delayed until after 1950 (Harris 1984). The harvest rate reached a peak in 1985 and has subsequently fallen dramatically to accommodate the conditions of the Northwest Forest Plan (Garman and others 1999).

NPP/NEP Analysis

The mean NPP was higher in the West Cascades (684 g C/m^2/year) than in the Coast Range (571 g C/m^2/year). This difference was primarily a reflection of differences in age class distribution rather than differences in the productive potential of the forests in the two geographical areas (Law and others in press). A much larger proportion of the Coast Range area was in the early regeneration phase (age < 14) compared to the West Cascades. The simulated NPP is relatively low in this class; hence, the overall mean NPP is lower. There was more area in the mature and old classes in the West Cascades, but the NPP remains relatively high in those stands, so the impact on mean NPP was not large (Acker and others 2000, 2002).

Differences in the productive potential were indicated in the conifer age sequence by a more rapid recovery of the maximum NPP in the Coast Range. The older regeneration class (age 14–29) had a mean NPP

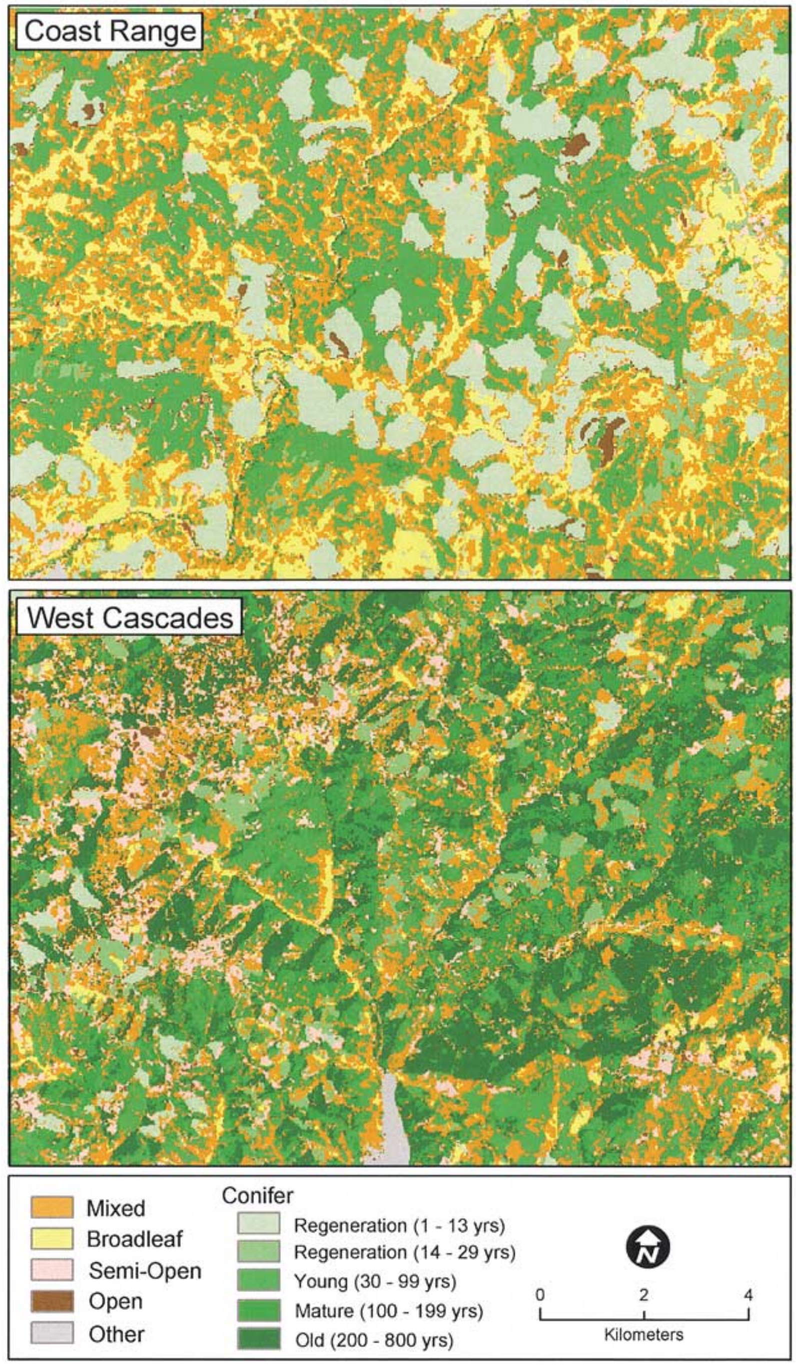


Figure 4. Land cover over the two study areas.

of 824 g C/m^2/year in the Coast Range compared to 601 g C/m^2/year in the West Cascades. The faster recovery of NPP in the Coast Range may be due to more favorable climatic conditions (Runyon and others 1994) as well as higher nitrogen availability. Foliar nitrogen concentrations for conifers are generally higher in the Coast Range than in the West Cascades (Law and others in press). In the Old class, mean NPP values were only marginally higher in the Coast Range. Law and others (in press) found good agreement between the NPP modeled by Biome-BGC and the measured NPP at 36 sites in a set of 3 chronosequences in western Oregon (slope of 1 to 1 line = 1.1, R^2 = 0.73).

The mean NPP in nonconifer-cover classes was lower in the Coast Range (Table 2) despite generally more favorable growing conditions, and the presence of the

Table 2. Modeled NPP by cover class.

Cover type	Coast Range Mean (g C/m²/year)	Coast Range SD	Coast Range Total (g C × 10^6)	West Cascades Mean (g C/m²/year)	West Cascades SD	West Cascades Total (g C × 10^6)
Conifer						
Regeneration (1–13)	160	35	4,752	439	164	1,097
Regeneration (14–29)	824	201	6,510	601	238	4,748
Young (30–99)	897	70	40,634	1,017	151	22,781
Mature (100–200)	845	54	3,126	802	56	29,273
Old (+200)	784	72	627	715	44	24,238
Broadleaf	491	97	11,195	752	86	1,221
Mixed	546	49	25,061	622	61	17,108
Semiopen	262	52	1,729	455	84	11,134
Open	239	10	526	313	86	1,278
Other	—	—	—	—	—	—
Total			94,160			112,878

Note: Ranges for stand age are given for conifer classes. The total NPP is the product of the area and the mean value.

Table 3. Modeled NEP by cover class

Cover type	Coast Range Mean (g C/m²/year)	Coast Range SD	Coast Range Total (g C × 10^6)	West Cascades Mean (g C/m²/year)	West Cascades SD	West Cascades Total (g C × 10^6)
Conifer						
Regeneration (1–13)	−6	14	−178	−142	47	−355
Regeneration (14–29)	389	92	3,073	254	98	2,007
Young (30–99)	299	22	13,545	354	69	7,930
Mature (100–200)	84	6	311	82	14	2,993
Old (+200)	47	4	38	49	8	1,661
Broadleaf	202	42	4,606	320	72	1,248
Mixed	230	21	10,557	265	27	9,964
Open	99	4	218	134	35	228
Semiopen	109	22	719	193	35	3,455
Other	—	—	0	—	—	0
Total			32,889			29,171

Note: Ranges for stand age are given for conifer classes. The total NPP is the product of the area and the mean value.

nitrogen-fixing alder. This pattern was driven primarily by lower LAIs as indicated by remote sensing. There has been relatively little validation of the LAI and NPP differences for the nonconifer-cover classes in these study areas and this uncertainty should be addressed in future studies.

The mean NEP (Table 3, Figure 5) was 199 g C/m²/year for the Coast Range area compared to 177 g C/m²/year for the West Cascades area. The most negative NEPs were in the early regeneration class (ages 1–13) of conifers in the West Cascades, where a slow recovery of NPP did not provide a strong enough carbon sink to overcome the carbon source associated with decomposing harvest residues. The maximum NEP was in the Coast Range in the older conifer regeneration class (ages 14–29), where the LAI had fully recovered and the carbon source from decomposing residues had significantly declined.

Estimates of the NEP are more difficult to evaluate than the NPP because of the greater uncertainty about the measured NEP. Quantifying the NEP requires estimates of carbon budget components that each have associated errors (Law and others in press). For the modeled values, one of the greatest uncertainties is the amount of wood debris left after the harvest. Annual NEP estimates are increasingly being made at eddy covariance flux tower sites and these values will provide additional opportunities for model validation (e.g., Law and others 2000).

As with the NPP, the age class distribution of the stands strongly influences the mean NEP estimates. The large areas of low NEP mature and old conifer in

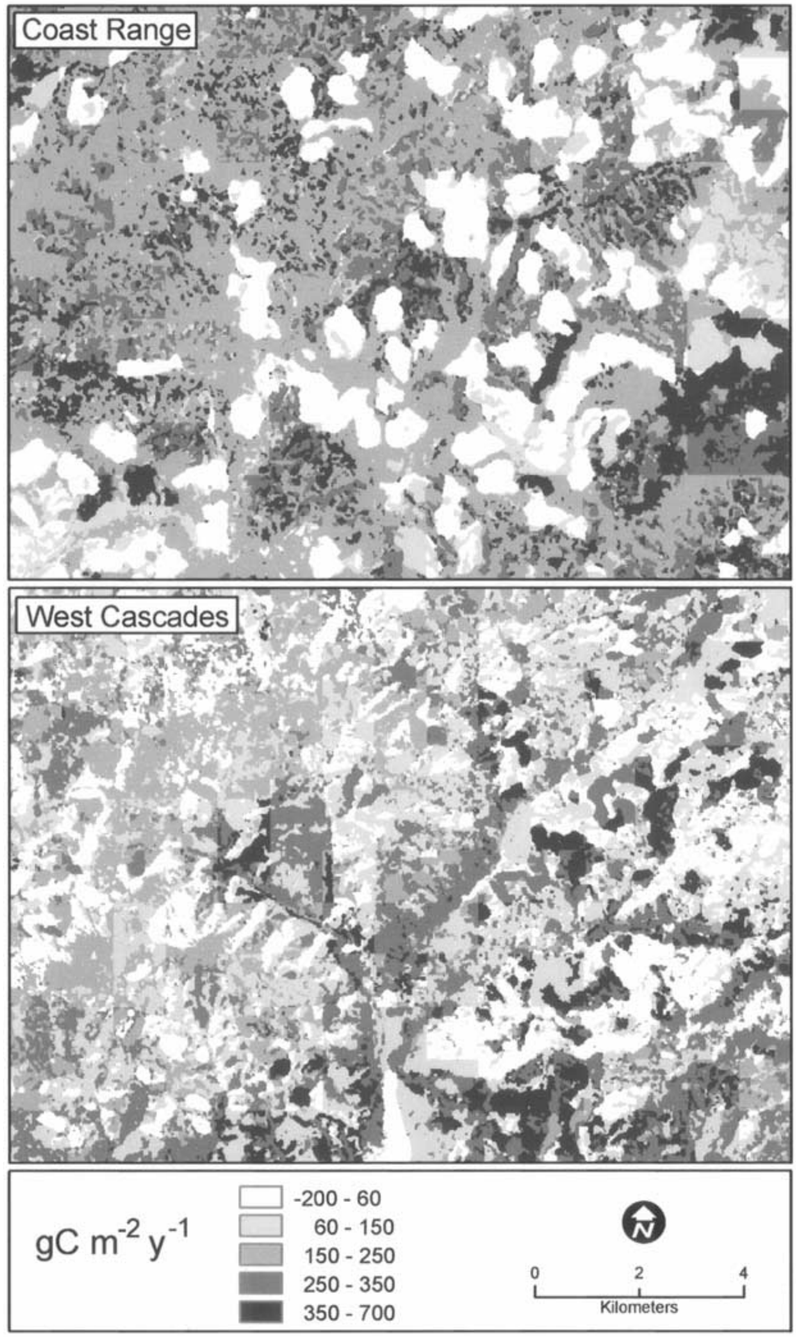


Figure 5. The distribution of NEP over the two study areas.

the West Cascades area tended to reduce the area wide mean NEP value. There was also about three times as much area in the highest NEP class (young) in the Coast Range, which tended to give it a higher NEP.

Land-Base Carbon Flux

The area harvested between 1991 and 2000 in the Coast Range study area was a significant proportion of the total area (16.9%). That pattern is consistent with the transition to predominantly short-rotation plantation forestry in the Coast Range (Rasmussen and Ripple 1998; Garman and others 1999). Virtually no harvesting (< 1% of the area) occurred during that period in the West Cascades. Most of the West Cascades area is in the Willamette National Forest and was subject to a legally mandated reduction in harvest in the 1990s.

Thus, the average rate of removal over the study area was −364 g C/m^2/year in the Coast Range and −7 g

Table 4. Land-base carbon budgets for the two study areas

Study area	A (NEP)	B (Harvest removals)	C (NBP) (A−B)
Coast Range	199	−364	−165
West Cascades	177	−7	170

Note: Units are the mean g C/m^2/year over the study area.

C/m^2/year in the West Cascades. The uncertainties associated with the removal estimates are principally related to estimates of the aboveground tree carbon at a given location before harvesting. That uncertainty is minimized to some degree in this study because most of the harvested area was on private lands that are managed for wood production with a relatively short-rotation age. In areas where older forests were being harvested, it would be important to use the remote-sensing-based estimates of stand age together with stand-level carbon budgets (Turner and others 1995) to refine removal estimates.

An alternative means of estimating harvest removals over large areas is associated with the periodic Resource Protection Act (RPA) Assessments (e.g., Powell and others 1993). There, the growing stock removal estimates are based on a combination of estimates derived from resurveys of the Forest Inventory and Analysis (FIA) permanent plot network and research efforts to track reported harvests. These values are reported at the scale of regions within the United States over time intervals on the order of 5 years. The remote sensing approach has the advantage of being spatially and temporally explicit. Early efforts to match inventory-based removal estimates and remote-sensing-based estimates have found relatively poor agreement (Wallin and others 1996), but uncertainties around estimates from both approaches are high.

The average accumulation of carbon over large areas and/or long periods is referred to as net biome productivity (NBP) (Steffen and others 1998). Here, the NBP is calculated as the balance of the NEP and harvest removals (Table 4). In the Coast Range study area, the NBP was −165 g C/m^2/year; that is, the land base was losing carbon over the study period. This effect is expected during the transition from predominantly primary forest (i.e., not previously cut) to predominantly secondary forests (Harmon and others 1990). Another factor tending to reduce mean carbon storage in the heavily managed Coast Range is the trend toward shorter rotations. As the average stand age declines, the mean carbon storage on the landscape also declines (Cooper 1983; Harmon 2001).

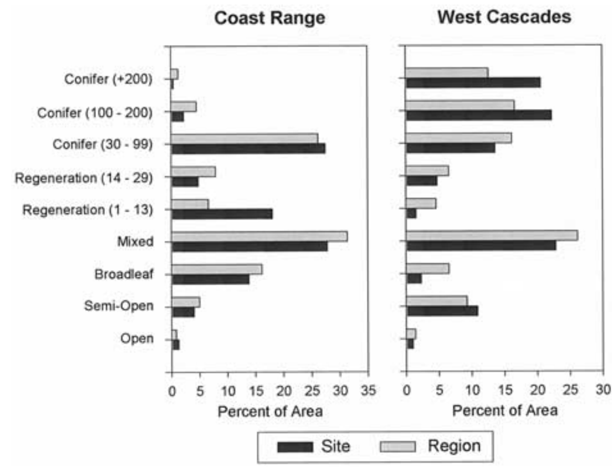


Figure 6. The proportional representation of the land-cover types in the study areas and their respective ecoregions.

The 165-km^2 Coast Range study area examined in this study was selected to emphasize the condition under intensive management. As part of a larger study, the remote-sensing-based land-cover analysis was also performed over all of western Oregon (Law and others in press). For a 19,362-km^2 area that included most of the Coast Range ecoregion, the proportion of the area in the conifer young regeneration class (i.e., harvested in the last 13 years) was only 37% of that in the study area (Figure 6). If the average rate of carbon removal was correspondingly smaller (−135 g C/m^2/year), then for the Coast Range land base as a whole, there would be an approximate balance in annual NEP and wood removal.

In the West Cascades study area, there was very little harvest removal of carbon (Table 4). Thus, most of the carbon accumulation associated with the NEP remained on the land base (177 g C/m^2/year). For a 14,620-km^2 area in the West Cascades ecoregion, the proportion of the land in the conifer young regeneration class was somewhat higher (4.6%) than in the study area (1.5%), so the average rate of sequestration in the ecoregion may be a little lower (Figure 6). Much of the accumulation is in relatively young stands recovering from earlier clearcuts. The continued sequestration of carbon in the West Cascades ecoregion is likely to eventually be terminated by a fire that would release some or most of the carbon accumulated in trees and coarse woody debris back to the atmosphere.

In addition to the carbon balance of the land base, the fate of carbon sequestered in harvested wood products must also be treated in evaluations of forests and greenhouse gas accounting (Harmon and others 1996a; Turner and others 1997). A significant proportion of merchantable wood removed from the land base is returned to the atmosphere during processing, some is converted to products with a relatively short turnover time and returned to the atmosphere within approximately 5 years (e.g., paper products), and some is converted into pools with long turnover times, such as wood in buildings. In the Pacific Northwest, carbon is accumulating in long-term storage pools at a rate of about 25% of the wood harvested (Harmon and others 1996b).

Conclusions

Satellite remote sensing in combination with spatially distributed carbon-cycle modeling shows promise for monitoring of land-base carbon flux at high spatial (30 m) and temporal (3–5 years) resolutions. Both the NEP and harvest removal components of a land-base carbon budget are treated. In western Oregon, this approach revealed areas of intensively managed forest that tended to lose carbon or be near the carbon steady state with respect to the land base (however, they were carbon sinks in terms of storage of long-lived forest products). Areas with relatively little harvesting in the last 10 years had an older stand-age class distribution and were significant carbon sinks.

Acknowledgements

This study was funded by US Environmental Protection Agency–Science to Achieve Results (STAR) Program (grant No. R-82830901-0). Special thanks to Peter Thornton (National Center for Atmospheric Research) for providing the Biome-BGC model and the 1980–1997 climate data.

References

Acker, S. A., P. A. Harcombe, M. E. Harmon, and S. E. Greene. 2000. Biomass accumulation over the first 150 years in coastal Oregon *Picea–Tsuga* forest. *Journal of Vegetation Science* 11:725–738.

Acker, S. A., C. B. Halpern, M. E. Harmon, and C. T. Dyrness. 2002. Trends in bole biomass accumulation, net primary production and tree mortality in *Psuedotsuga menziesii* forests of contrasting age. *Tree Physiology* 22:213–217.

Birdsey, R. A., A. J. Plantinga, and L. S. Heath. 1993. Past and prospective changes in U.S. forest ecosystems. *Forest Ecology and Management* 58:33–40.

Bosquet, P., P. Peylin, P. Ciais, C. L. Quere, P. Friedlingstein, and P. P. Tans. 2000. Regional changes in carbon dioxide fluxes of land and oceans since 1980. *Science* 290:1342–1346.

Cohen, W. B., T. A. Spies, and M. Fiorella. 1995. Estimating the age and structure of forests in a multi-ownership landscape of western Oregon, U.S.A. *International Journal of Remote Sensing* 16:721–746.

Cohen, W. B., M. E. Harmon, D. O. Wallin, and M. Fiorella. 1996. Two decades of carbon flux from forests of the Pacific Northwest. *BioScience* 46:836–844.

Cohen, W. B., M. Fiorella, J. Gray, J. E. Helmer, and K. Anderson. 1998. An efficient and accurate method for mapping forest clearcuts in the Pacific Northwest using Landsat imagery. *Photogrammetric Engineering and Remote Sensing* 64:283–300.

Cohen, W. B., T. A. Spies, R. J. Alig, D. R. Oetter, T. K. Maiersperger, and M. Fiorella. 2002. Characterizing 23 years (1972–95) of stand replacement disturbance in western Oregon forests with Landsat imagery. *Ecosystems* 5:122–137.

Cooper, C. F. 1983. Carbon in managed forests. *Canadian Journal of Forest Research* 13:155–166.

Garman, S. L., F. J. Swanson, and T. A. Spies. 1999. Past, present, future landscape patterns in the Douglas-fir region of the Pacific Northwest. Pages 61–86 *in* J.A. Rochelle, L. A. Lehmann, and J. Wisniewski. Eds, Forest fragmentation: Wildlife and management implications. Brill Academic Publishing, The Netherlands.

Grier, C. C., and S. R. Running. 1977. Leaf area of mature northwestern coniferous forests: relation to site water balance. *Ecology* 58:893–899.

Harmon, M. E. 2001. Carbon sequestration in forests: Addressing the scale question. *Journal of Forestry* 99:24–29.

Harmon, M. E., W. K. Ferrell, and J. F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. *Science* 247:699–7002.

Harmon, M. E., S. L. Garman, and W. K. Ferrell. 1996a. Modeling historical patterns of tree utilization in the Pacific Northwest: carbon sequestration implications. *Ecological Applications* 6:641–652.

Harmon, M. E., J. M. Harmon, W. K. Ferrell, and D. Brooks. 1996b. Modeling carbon stores in Oregon and Washington forest products: 1900–1992. *Climate Change* 33:521–550.

Harris, L. D. 1984. The fragmented forest. University of Chicago Press, Chicago, Illinois.

Kimball, J. S., S. W. Running, and S. S. Saatchi. 1999. Sensitivity of boreal forest regional water flux and net primary production simulations to sub-grid scale landcover complexity. *Journal of Geophysical Research* 104:27,789–27,801.

Law, B. E., R. H. Waring, P. M. Anthoni, and J. D. Aber. 2000. Measurements of gross and net ecosystem productivity and water vapor exchange of a *Pinus ponderosa* ecosystem, and an evaluation of two generalized models. *Global Change Biology* 6:155–168.

Law, B. E., P. E. Thornton, J. Irvine, P. M. Anthoni, and S. Van Tuyl. 2001. Carbon storage and fluxes in ponderosa pine forests at different developmental stages. *Global Change Biology* 7:1–23.

Law, B. E., Turner, P. P., Campbell, J. , Lefsky, M. S., Guzy, M. S., Sun, O., Van Tuyl, Harmon M., and Cohen, M. In press. Carbon fluxes across regions: Observational constraints at multiple scales. *In* J. Wu, B. Jones, H. Li, and O.

Loucks (eds.), *Scaling and uncertainty analysis in ecology: Methods and applications.* Columbia University Press, New York.

Parson, E. A., P. M. Haas, and M. A. Levy. 1992. A summary of the major documents signed at the Earth Summit and the Global Forum. *Environment* 34:12–15.

Powell, D. S., Faulkner,J. L., Darr, D. R., MacCleery, Z. Zhu, and D. W. 1993. Forest Resources of the United States, 1992. USDA Forest Service. General Technical Report RM-234. Washington, DC.

Rasmussen, M. C., and W. J. Ripple. 1998. Retrospective analysis of forest landscape patterns in western Oregon. *Natural Areas Journal* 18:151–163.

Richards, F. 1959. A flexible growth function for empirical use. *Journal of Experimental Botany* 10:290–300.

Runyon, J., R. H. Waring, S. N. Goward, and J. M. Welles. 1994. Environmental limits on net primary production and light use efficiency across the Oregon transect. *Ecological Applications* 4:226–237.

Schimel, D. S., and C. S. Potter. 1995. Process modeling and spatial extrapolation. Pages 358–383 *in* P. A. Matson, and R. C. Harriss. Eds, Biogenic trace gases: Measuring emissions from soil and water. Blackwell Science, Oxford.

Spanner, M. A., L. Johnson, J. Miller, and others. 1994. Remote sensing of seasonal leaf area index across the Oregon transect. *Ecological Applications* 4:258–271.

Spies, T. A., W. J. Ripple, and G. A. Bradshaw. 1994. Dynamics and pattern of a managed coniferous forest landscape in Oregon. *Ecological Applications* 4:555–568.

Sprugel, D. G. 1985. Natural disturbances and ecosystem energetics. Pages 335–352 *in* S. T. A. Pickett, and P. S. White. Eds, The ecology of natural disturbances and patch dynamics. Academic Press, New York.

Steffen, W., I. Noble, J. Canadell, M. Apps, E.-D. Schulze, P. G. Jarvis, D. Baldocchi, P. Ciais, W. Cramer, J. Ehleringer, G. Farquhar, C. B. Field, A. Ghazi, R. Gifford, M. Heimann, R. Houghton, P. Kabat, C. Körner, E. Lambin, S. Linder, H. A. Mooney, D. Murdiyarso, W. M. Post, C. Prentice, M. R. Raupach, D. S. Schimel, A. Shvidenko, and R. Valentini. 1998. The terrestrial carbon cycle: Implications for the Kyoto protocol. *Science* 280:1393–1394.

Thornton, P. E., and S. W. Running. 1999. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. *Agricultural and Forest Meteorology* 93:211–228.

Thornton, P. E., S. W. Running, and M. A. White. 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. *Journal of Hydrology* 190:214–251.

Thornton, P. E., H. Hasenauer, and M. A. White. 2000. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: An application over complex terrain in Austria. *Agricultural and Forest Meteorology* 104:255–271.

Thornton, P. E., B. E. Law, H. L. Gholz, K. L. Clark, E. Falge, D. S. Ellsworth, A. H. Goldstein, R. K. Monson, D. Hollinger, M. Falk, J. Chen, and J. P. Sparks. 2002. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needeleaf forests. *Agricultural and Forest Meteorology* 113:185–222.

Turner, D. P., G.J. Koerper, M. E. Harmon, and J. J. Lee. 1995. A carbon budget for forests of the conterminous United States. *Ecological Applications* 5:421–436.

Turner, D. P., J. K. Winjum, T. P. Kolchugina, and M. A. Cairns. 1997. Accounting for biological and anthropogenic factors in national land-base carbon budgets. *Ambio* 26:220–226.

Turner, D. P., W. B. Cohen, R. E. Kennedy, K. S. Fassnacht, and J. M. Briggs. 1999. Relationships between leaf area index and TM spectral vegetation indices across three temperate zone sites. *Remote Sensing of Environment* 70:52–68.

Turner, D. P., W. B. Cohen, and R. E. Kennedy. 2000. Alternative spatial resolutions and estimation of carbon flux over a managed forest landscape in western Oregon. *Landscape Ecology* 15:441–452.

Turner, D. P., M. Guzy, M. A. Lefsky, S. VanTuyl, O. Sun, C. Daly, and B. E. Law. 2003. Effects of land use and fine scale environmental heterogeneity on net ecosystem production over a temperate coniferous forest landscape. *Tellus* 55B:657–668.

UN FCCC. 1992. United Nations Framework Convention on Climate Change; available at www.unfccc.de/resource/conv/index.html.

USDA Forest Service. 2001. RPA Assessment of forest and range lands. Report No. FS-687. USDA Forest Service, Washington, D/C, 78 pp.

Wallin, D. O., Harmon, M.E., Cohen, W. B., Fiorella, M., and Ferrell, W. K. 1996. Use of remote sensing to model land use effects on carbon flux in forests of the Pacific Northwest, USA. Pages 219–237 *in* H.L. Gholz, K. Nakane, and H. Shimoda (eds.), *The use of remote sensing in the modeling of forest productivity at scales from the stand to the globe.* Kluwer Academic P, Dordrecht Netherlands.

White, M. A., P. E. Thornton, S. W. Running, and R. Nemani. 2000. Parameterization and sensitivity analysis of the BIOME-BGC terrestrial ecosystem model: Net primary production controls. *Earth Interactions* 4:1–85.