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Alternative spatial resolutions and estimation of carbon flux over a managed forest landscape in Western Oregon

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Abstract

Spatially-distributed estimates of biologically-driven CO_2 flux are of interest in relation to understanding the global carbon cycle. Global coverage by satellite sensors offers an opportunity to assess terrestrial carbon (C) flux using a variety of approaches and corresponding spatial resolutions. An important consideration in evaluating the approaches concerns the scale of the spatial heterogeneity in land cover over the domain being studied. In the Pacific Northwest region of the United States, forests are highly fragmented with respect to stand age class and hence C flux. In this study, the effects of spatial resolution on estimates of total annual net primary production (NPP) and net ecosystem production (NEP) for a 96 km^2 area in the central Cascades Mountains of western Oregon were examined. The scaling approach was a simple ‘measure and multiply’ algorithm. At the highest spatial resolution (25 m), a stand age map derived from Landsat Thematic Mapper imagery provided the area for each of six forest age classes. The products of area for each age class and its respective NPP or NEP were summed for the area wide estimates. In order to evaluate potential errors at coarser resolutions, the stand age map was resampled to grain sizes of 100, 250, 500 and 1000 m using a majority filter reclassification. Local variance in near-infrared (NIR) band digital number at successively coarser grain sizes was also examined to characterize the scale of the heterogeneity in the scene. For this managed forest landscape, proportional estimation error in land cover classification at the coarsest resolution varied from -1.0 to $+0.6$ depending on the initial representation and the spatial distribution of the age class. The overall accuracy of the 1000 m resolution map was 42% with respect to the 25 m map. Analysis of local variance in NIR digital number suggested a patch size on the order of 100–500 m on a side. Total estimated NPP was 12% lower and total estimated NEP was 4% lower at 1000 m compared to 25 m. Carbon flux estimates based on quantifying differences in total biomass stored on the landscape at two points in time might be affected more strongly by a coarse resolution analysis because the differences among classes in biomass are more extreme than the differences in C flux and because the additional steps in the flux algorithm would contribute to error propagation. Scaling exercises involving reclassification of fine scale imagery over a range of grain sizes may be a useful screening tool for stratifying regions of the terrestrial surface relative to optimizing the spatial resolution for C flux estimation purposes.

Introduction

Spatially-explicit analyses of ecosystem carbon flux are required for understanding the current global carbon (C) cycle (Schimel 1995a). Because of its broad spatial coverage, satellite remote sensing has been used in a variety of approaches to estimate various components of terrestrial C flux. In the ‘measure and multiply’ approach (Schimel and Potter 1995) for net primary production (NPP) and net ecosystem production (NEP), the area of each vegetation type derived from remote sensing is multiplied by a representative C flux for that vegetation type. In the ‘difference’ approach, remote sensing has been used to monitor changes in land cover associated with deforestation (Riley et al. 1997) or forest harvest (Cohen et al. 1996) and C flux is estimated as the difference in total C storage over the landscape at two points in time divided by the interval between image acquisitions. A more process-based approach involves application of spatially-distributed biogeochemistry models for NPP and NEP which are initialized with land cover type and leaf area index from remote sensing (Hunt et al. 1996). Alternatively, a theoretical or empirical light use efficiency factor can be used for estimation of NPP over large areas when estimates of absorbed photosynthetically active radiation are derived from remote sensing (Prince and Goward 1995). The spatial resolution or grain size in the studies employing these approaches has largely been determined by the specifications of the particular sensor used in the study which ranges from the 30 m resolution of the TM (Thematic Mapper) sensor to the 8 km resolution of the global AVHRR (Advanced Very High Resolution Radiometer) Pathfinder data set. The degree to which sensor resolution contributes to uncertainty in these studies has generally not been addressed.

The Moderate Resolution Imaging Spectrometer (MODIS) sensor, intended to be the primary instrument for global observation of the terrestrial surface in the Earth Observing System (EOS) era (Justice et al. 1998), will have a spatial resolution on the order of 250–1000 m depending on the spectral band. This range of resolutions was a compromise between the desire for daily global coverage, which has proved useful in applications of AVHRR data to monitoring of vegetation phenology (Justice et al. 1985) and classification of land cover (Loveland et al. 1991), and the desire for high spatial resolution for monitoring of land cover change. The compromise is forced by the technical constraints related to processing and storing the associated digital data. Significant spatial heterogeneity in land surface properties may nevertheless occur at spatial resolutions finer than 250–1000 m in many areas, and a number of studies have investigated how accuracy in characteristics such as land cover classification is affected by the spatial resolution of the analysis (Townsend and Justice 1988; Moody and Woodcock 1995). As the EOS era efforts to monitor terrestrial NPP globally based on satellite imagery are implemented (Running et al. 1999), it will be important to investigate the role of spatial resolution on accuracy at local validation sites (Reich et al. 1999).

The coniferous forests of the Pacific Northwest (PNW) region are of particular interest with respect to the C cycle. Accumulations of living and dead biomass are among the highest in the world, thus logging creates both a large C source from burning and decomposition of logging residue and C sinks from long lived forest products (Harmon et al. 1990; Cohen et al. 1996). Productivity rates are also relatively high in many areas (Waring and Franklin 1979; Grier et al. 1989) which creates large C sinks when rates of logging are moderated, as has been the case on public lands recently (Haynes et al. 1995). Because much of the forested land in the PNW region is public and was managed under a system of small dispersed clearcuts over the last several decades, there is a significant degree of spatial heterogeneity in stand age class (Wallin et al. 1996). The region is thus pertinent for a case study of the interacting effects of landscape pattern and sensor resolution in carbon flux estimation.

In this study, we examined a 96 km^2 sample of a managed forest landscape in the PNW at spatial resolutions from 25 m to 1000 m to evaluate potential influences of spatial resolution on estimates of NPP, NEP, and biomass C using a measure and multiply approach. The 96 km^2 represents an area large enough to provide a basis for comparison with the gridded annual NPP product from MODIS (Running et al. 1999). The scaling exercise performed here was intended as a step towards development of screening tools for stratifying the Earth’s surface in relation to the appropriate resolution for particular satellite-based C flux estimation algorithms.

Methods

In the measure and multiply algorithm for scaling biogenic trace gas fluxes from points to landscapes or regions, the land cover over the spatial domain of interest is classified with respect to some factor which strongly regulates biogenic trace gas flux and for which a map is available. In this study our interest was in estimating annual NPP and NEP over a 96 km^{2}area of predominantly coniferous forest. Biomass C was also estimated because of its use in the difference approach flux algorithm. One factor strongly related to C pools and flux in these forests is stand age class (Turner et al. 1995) and a high spatial resolution (25 m) digital map of stand age class derived from satellite remote sensing was available for the study area (Cohen et al. 1995). NPP, NEP and biomass C estimates for each stand age class were therefore multiplied by the respective areas of each age class at each of five grain sizes (25 m, 100 m, 250 m, 500 m, 1000 m) to get totals for the study area.

A simple majority filter, here an analogue for image classification at a coarser resolution, was used to assign an age class to each grid cell at the coarser resolutions. In the majority rule aggregation algorithm, the cover type with the greatest frequency of 25 m subcells in the coarser resolution cell determines the label for the coarse resolution cell. In the case of a tie, a random selection is made among the subcells. The aggregation procedure in this study was implemented with the IDL programming language rather than with a standard Geographic Information Systems software package because the latter sometimes attempt to preserve the initial proportional representation during aggregation. Alternative aggregation algorithms, such as selection of a random subcell to represent the coarse resolution cell, may do a better job at preserving the overall proportions and the representation of cover classes having small areas (e.g., Milne and Johnson 1993), but the focus here was primarily on mimicking how a coarse resolution sensor would see the landscape. To whatever degree spectral mixing within a pixel is nonlinear, the misclassification with a coarse resolution sensor could be greater than is indicated by the majority filter analogue.

As a step towards evaluating the influence of the abundance and distribution of particular cover classes to the total error at each grain size, the proportional estimation error (Moody and Woodcock 1994) for each cover class at each grain size was determined. To characterize the scale of the heterogeneity in the study area, a local variance analysis (Woodcock and Strahler 1987) was also run on near-infrared digital number numbers across the range of grain sizes.

The study area

A 7 km × 14 km area centered on the H.J. Andrews Experimental Forest in western Oregon (Van Cleeve and Martin 1991) was studied. Approximately 80% of the study area is in the western hemlock (*Tsuga heterophylla*)/Douglas-fir (*Pseudotsuga menziesii*) zone and 20% in the silver fir (*Abies amabalis*) zone (Franklin and Dyrness 1990). About half the study area is native forest (Cohen et al. 1995) and the remainder has been harvested over the last 50 years, mostly in the form of small ($<$ 40 ha) clearcuts (Cohen et al. 1998). The landscape pattern in the study area is representative of much of the nonwilderness National Forest land in the PNW.

The forest age class distribution in 1988 was mapped using Landsat Thematic Mapper imagery (Cohen et al. 1995). In the mapping analysis, six vegetation cover classes and a water class were recognized in the study area (Table 1). The classes approximated the successional sequence expected in mid-elevation forests in this region (Franklin and Spies 1991). The closed-mixed class is known to contain areas of closed canopy forest which are mixtures of conifer and hardwood trees (e.g., riparian area) as well as mixtures of tall shrubs and young conifer trees in recovering clearcuts. For the purposes of this scaling exercise, however, this class was considered intermediate between the semi-open class and the young conifer class in the successional sequence.

NPP, NEP and biomass by stand age class

The development of the representative NPP, NEP, and biomass estimates for each stand age class (Table 1) was based on studies of PNW Douglas-fir forests in the literature and generalized trends expected in forest stand development (Bormann and Likens 1979; Cropper and Ewel 1984; Sprugel 1985). Stand level carbon budgets which treat the changes in biomass, wood production, and NEP over the course of stand development, had been prepared previously for all major forest types in the U.S. (Turner et al. 1995). This study used the C budget for medium productivity Douglas-fir stands in the West Cascades. For each of the 6 stand age classes, the biomass C and flux estimates for the age at the middle of that class were used for representative values. Foliar/fine litter production and fine root production were then estimated from allometric relationships (Turner and Long 1977; Grier and Logan 1977; Gholz et al. 1985; Vogt 1991).

In the decades after a clear-cut harvest, C uptake via NPP is typically low in this region as vegetation recovers, whereas C emissions associated with heterotrophic respiration are high because of decomposition of logging residue. Thus NEP, the net effect of photosynthesis and both autotrophic and heterotrophic respiration, is negative (a source of carbon to the atmosphere) during this stage. About the time of canopy closure, NPP is near its maximum and heterotrophic respiration has decreased, hence, the NEP is also maximal. In late succession, NPP typically decreases and

Table 1. Land cover classes in the study area distinguished by satellite remote sensing (Cohen et al. 1995) and representative values for net primary production (NPP), net ecosystem production (NEP), total biomass carbon, and total biomass carbon range (Turner and Long 1975, Turner et al. 1995).

Class	Cover (%)	Approximate Age (yrs)	NPP gC m^{-2} yr^{-1}	NEP gC m^{-2} yr^{-1}	Biomass MgC ha^{-1}	Biomass Range MgC ha^{-1}
Water	–	–	–	–	–	–
Open	< 30	0–10	283	-210	3.5	2.6–4.3
Semi-closed	30–85	10–20	511	-116	10.5	8–13
Closed-mixed	> 85	20–30	698	159	42.5	24–44
Closed conifer						
Young	> 85	< 80	1036	473	106	42–117
Mature	> 85	80–200	798	286	246	91–264
Old	> 85	> 200	444	165	435	304–607

heterotrophic respiration increases, so NEP tends to decrease.

NPP, NEP, and biomass certainly vary within an age class depending on harvest-related factors such as the degree of slash burning, climatic factors related to elevation and aspect, and site factors such as soil depth. However, that variation has not been well characterized so only representative values for each cover class were used in this study. Ranges of biomass for each class, based primarily on the stand level carbon budgets for low, medium and high productivity PNW west-side Douglas-fir stands (Turner et al. 1995), are indicated (Table 1).

Error assessment

The effects of coarsening the spatial resolution on agreement in the land cover classification were assessed overall as the percent of the coarse resolution map which was the same as the 25 m resolution map. Within each cover class the proportional estimation error (Moody and Woodcock 1994) at each resolution was determined as:

$$E_{\text{ir}} = (P_{\text{ir}} - P_{\text{io}})/P_{\text{io}}, \qquad (1)$$

where E_{ir} = Proportion estimation error of class *i* at resolution *r*; P_{ir} = Proportion of class *i* within the total scene at resolution *r*; P_{io} = Proportion of class *i* within the total scene at original resolution (25 m).

The effects of each coarser resolution on the C flux and biomass estimates was assessed as the difference between the totals for the whole study area at that resolution and at the 25 m resolution.

The local variance analysis

Local variance analysis (Woodcock and Strahler 1987) requires a continuous variable and was performed with the digital number (DN) for the near-infrared band of the Thematic Mapper sensor. The DN value for each grid cell is a measure of the reflected radiation for that cell as detected by the sensor. The image processing procedure is described in Cohen et al. (1995). Near-infrared reflectance is generally sensitive to leaf area (Price and Bausch 1995) and is likely to indicate variation in land cover type. Local variance was based on the standard deviation of DN for the 9 cells in a 3 × 3 cell moving window which was framed around each grid cell at the reference resolution in the image. The mean of the standard deviations from all complete 3 × 3 windows in the study area was then reported as the indicator of local variance. This analysis was run at resolutions of 25, 50, 100, 250, 500 and 1000 m. The aggregation rule for generating the coarser resolution surfaces was to take the mean value of the DNs in the aggregated cells.

Results

Visual inspection of the classified image of the study area at the 25 m resolution (Figure 1) indicates a pattern of patches in early stages of succession within a background of older forests. The water cells are in one polygon, a portion of a reservoir at the south edge of the study area. As the spatial resolution is coarsened from 25 m to 250 m, fine-scale heterogeneity within the polygons diminishes such that the fundamental patch structure imposed by forest harvesting becomes

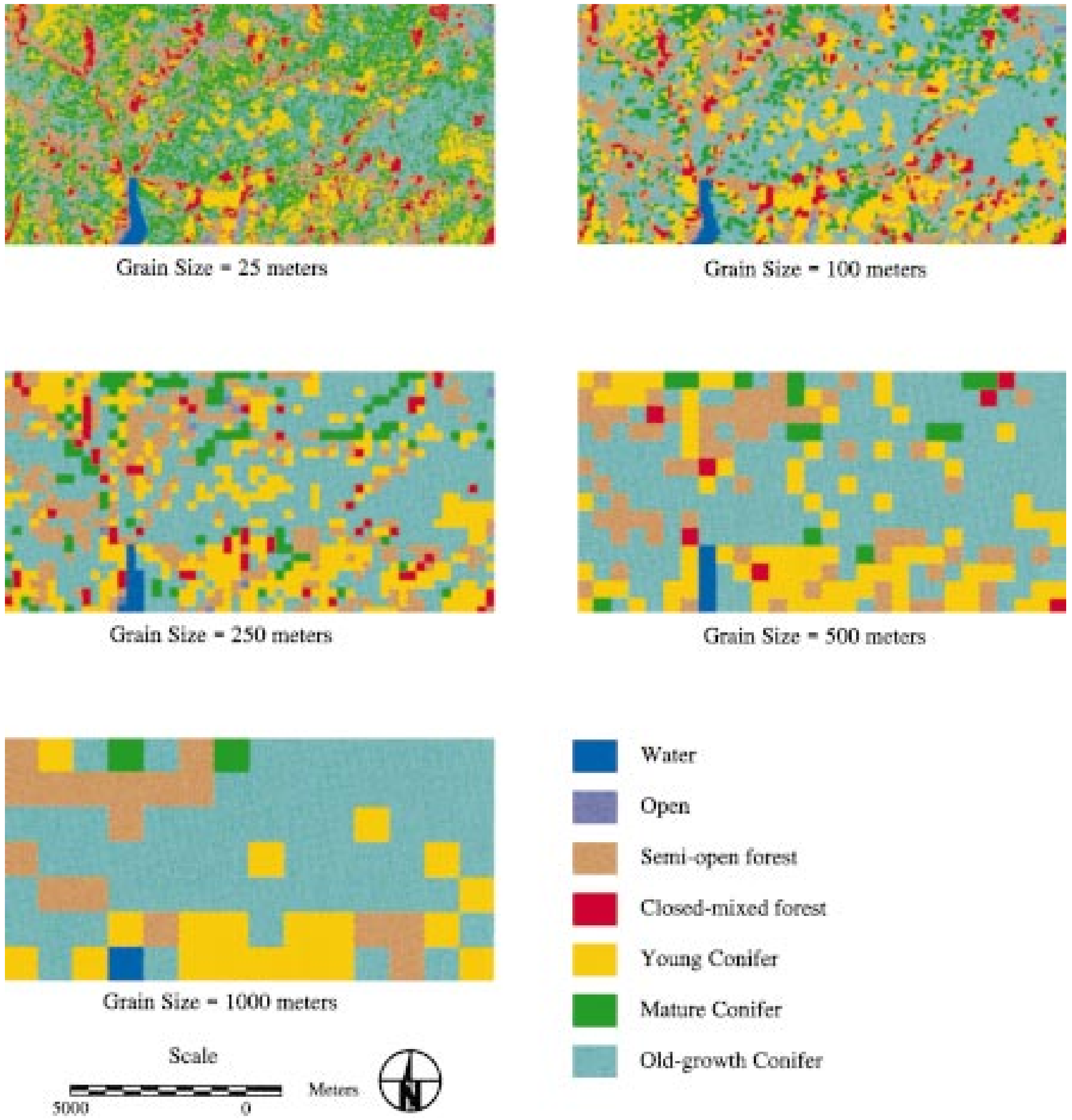

Figure 1. Classified image of the study area at successively coarser spatial resolutions

more obvious. As the resolution is coarsened above 250 m, clearcut patches begin to merge and the pattern imposed by harvesting is largely lost. Correspondingly, the local variance increased as spatial resolution was coarsened from 25 m to 250 m then decreased as the resolution was further coarsened (Figure 2).

The overall agreement with respect to the 25 m image rapidly decreased as the spatial resolution was coarsened and agreement was only 42% at the 1000 m resolution (Figure 3, Table 2). The rapid falloff in percent agreement as the spatial resolution was coarsened, despite more modest changes in areal proportions, reflects in part a speckling pattern at the finest spatial resolution. Since the area estimates in Table 2 are not spatially explicit, they do not reveal the shifting around induced by the aggregation.

The proportional estimation error ranged from 0.028 to −0.419 at 100 m (Figure 4) and the maxi-

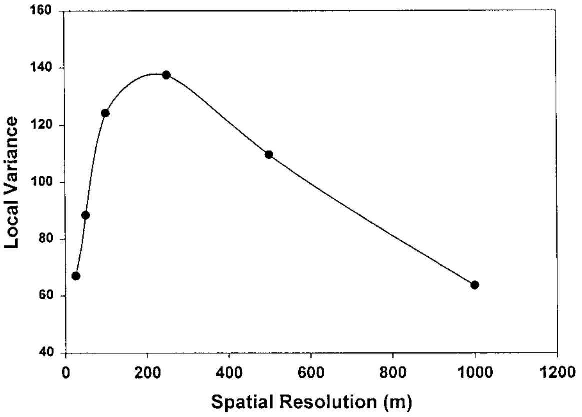

Figure 2. Local variance in near infra-red radiance at successively coarser spatial resolutions

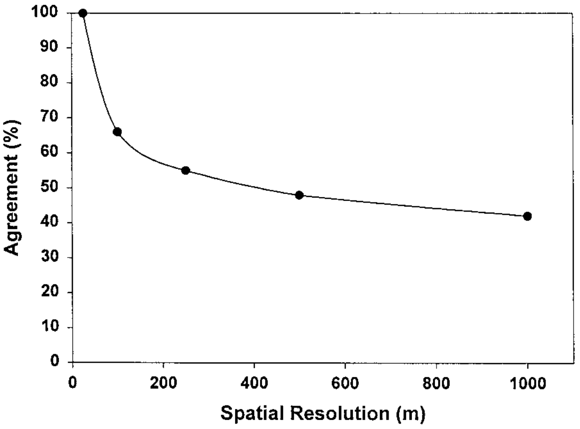

Figure 3. Percent agreement in land cover classification at successively coarser spatial resolutions. The percent refers to comparison with the base 25 m land cover surface.

Table 2. Effects of spatial resolution on areas (* 10^6 m^2) by cover class.

Cover type	Spatial resolution				
	25 m	100 m	250 m	500 m	1000 m
Water	0.769	0.810	0.875	1.000	1.000
Open	1.167	0.740	0.375	0.0	0.0
Semi-open	17.460	17.950	17.562	18.000	16.000
Closed-mixed	5.567	5.360	4.000	1.750	0.0
Young	20.092	20.880	22.062	20.250	19.000
Mature	17.019	9.880	6.062	3.500	2.000
Old-growth	35.925	42.380	47.062	53.50	60.000

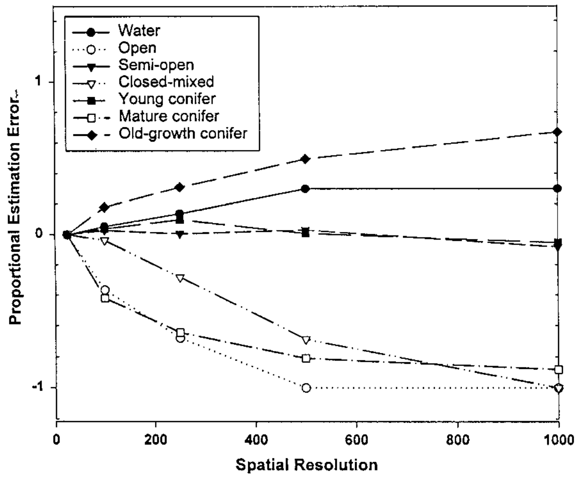

Figure 4. Trend in prportional estimation error as a function of spatial resolution of the land cover surface.

mum error increased to −0.679 at 250 m. At 500 m, the open class had been lost and at 1000 m the closed-mixed class was likewise no longer represented. Though least in areal extent at 25 m, the water class was retained at 1000 m because of the contiguous arrangement of its cells. The classes which were lost at 1000 m were the next two least represented land cover classes. The largest shifts in classification with coarsening of the resolution were the loss of the mature class and the gain of the old-growth class.

The estimates of NPP and NEP for the 96 km^2 area were 6.35×10^{10} g and 1.89×10^{10} g respectively at the 25 m resolution (Table 3). For NPP, the flux estimate consistently decreased with coarsening of the spatial resolution and was 12% lower at 1000 m than at 25 m. The decrease was primarily because the old-growth class has a lower representative NPP than the mature class and much of the loss of the mature conifer class was associated with a gain in area for the old-growth conifer class. The change in NEP with coarsening of the resolution was smaller than was the case with NPP because (1) the NEP of the old-growth and mature classes was more similar than their NPPs and (2) the smaller area of negative NEP classes (open and semi-open) at 1000 m tended to compensate for the error associated with shifts from mature to old-growth conifer.

The estimate for total tree biomass over the study area increased as the spatial resolution was coarsened (Table 3), and the estimate at 1000 m was 29% higher than that at 25 m. This change was primarily asso-

Table 3. Effects of spatial resolution on estimates of net primary production (NPP), net ecosystem production (NEP), and tree biomass carbon over the study area. Differences are relative to the area wide estimates at the 25 m resolution.

Resolution (m)	NPP		NEP		Tree biomass	
	Flux ($\times 10^{10}$ gC)	Difference (%)	Flux ($\times 10^{10}$ gC)	Difference (%)	Pool ($\times 10^{12}$ gC)	Difference (%)
25	6.35	–	1.89	–	2.24	–
100	6.15	−3	1.83	−3	2.35	5
250	6.05	−5	1.85	−2	2.47	10
500	5.79	−9	1.76	−7	2.66	19
1000	5.61	−12	1.76	−7	2.88	29

ciated with an increase in the area of the old-growth conifer class with its relatively high biomass.

Discussion

Scale dependence in land cover mapping

A variety of studies have examined the effects of employing alternative spatial resolutions on land cover assessments and estimates of terrestrial carbon flux. The objective is often to identify the optimal resolution for a particular application. Evaluations of land cover change in the Amazon Basin using the coarse resolution Global Area Coverage data products from the AVHRR sensor were shown to poorly estimate deforestation relative to higher resolution analyses based on the Landsat Multispectral Scanner (MSS) (Nelson and Holben 1986). Artificially degrading the resolution of MSS imagery from 250 m to 4000 m similarly led to greatly compromised ability to detect land cover changes in several locations studied by Townshend and Justice (1988). In the boreal region, intercomparison of land cover maps derived from AVHRR and TM indicated that AVHRR pixels were clearly mixtures of TM classes (Steyaert et al. 1997). One of the classes with greatest disagreement between the sensors was the regenerating forest class, which is particularly important for the purposes of C flux estimation. Information loss from aggregation of fine resolution data to coarser resolutions has also been investigated in the context of efficiently accumulating multitemporal data (Pax-Lenney and Woodcock 1997). As was evident from those studies and this study in PNW coniferous forests, the scale of human disturbance is often considerably less than 1 km and for the purposes of assessing land use change effects on the carbon cycle, resolutions down to 30 m will continue to be essential (Schimel 1995b).

In remote sensing analyses, one criteria for selecting spatial resolution is that it should be significantly smaller than the scale of the relevant heterogeneity over the domain of interest (Quattrochi and Pelletier 1991). The effect of following this maxim is that relatively few cells are mixtures of classes, and that edges may be distinguished as changes from dominance by one cell type to dominance by another. There is, however, likely to be a limit below which a new scale of heterogeneity becomes evident, as in a patch of conifer forest which appears homogeneous at 25 m resolution but heterogeneous at 1 m when individual tree crowns begin to be resolved (Cohen et al. 1998). Likewise, in a coarsening of the resolution, homogeneity may emerge as grid cells begin to incorporate uniform mixtures of patch types. Thus, there is no privileged spatial resolution, and the issue of scale dependence must often be addressed in mapping of land cover (Davis et al. 1991; Cao and Lam 1997).

The evaluation of proportional estimation error and local variance at multiple spatial resolutions provides a means of characterizing the scale of the heterogeneity in a remotely-sensed scene. In the PNW landscape examined here, there is a clear patch structure associated with the human-dominated disturbance regime. The local variance analysis indicated a maximum variance at about the 250 m resolution. Earlier studies have suggested that local variance peaks at a cell size somewhat smaller than the objects in the scene (Woodcock and Strahler 1987). Thus, the result in the PNW scene indicated patches on the order of 20 ha (400 m on a side) which approximates the size of clearcuts under the dispersed cutting scheme formerly favored by the U.S. Forest Service. The finest resolution (25 m) was still too large to resolve individual tree canopies, so each cell contained many trees and each window of 9 cells tended to be within one patch type resulting in low variance. At the 1000 m resolution, each cell tended to include a mixture of patches from different successional stages and again there was relatively low variance within the 9-cell windows.

The observation here that the classes with the smallest proportion of the stand area were lost as the resolution was coarsened is consistent with earlier studies of scale dependence in land cover mapping (Turner et al. 1989, 1996; Moody and Woodcock 1994, 1995). This trend is especially conspicuous when the patch sizes are relatively small and they are well dispersed, as was the case in this study. The cells classed as water were all in one patch and the effect of coarsening resolution was different from the other relatively small classes in that it was retained and grew as resolution was coarsened. This result indicates that the spatial distribution of a class is as important in its sensitivity to spatial resolution as is its absolute area.

Scale dependence in estimating C flux

Because the measure and multiply approach to C flux estimation relies on land cover mapping, the effects of proportional estimation error carry over into the associated C flux estimates. However, the correspondence in the magnitude of the error in terms of land areas and in terms of C flux will vary. Scale-dependent errors in C flux estimates would not be large where land cover types detectable by remote sensing had similar representative NPP or NEP. The annual NPP of a corn field and a soybean field may be similar, in which case mixtures of those land cover classes within a grid cell would not need to be resolved into separate classes for an accurate landscape-level estimate of NPP. As the range of the class-specific C flux values widens though, the potential for error in flux estimates at coarser resolutions increases. As noted, the larger error in this study at 1000 m in the NPP estimate compared to the NEP estimate reflected in part the greater difference in the range of NPP values between mature conifer and old-growth conifer classes compared to the range of NEP values. Differences between land cover types in the flux of trace gases such as methane (Aselmann and Crutzen 1989) and nitrous oxide (Bouwman et al. 1995) are also large, so issues related to spatial resolution will similarly be important in mapping of fluxes for those trace gases based on land cover type.

Scale dependent errors in C flux estimates similar to those found in the PNW would be less likely where land cover classification is less scale dependent. Large areas of the Amazon Basin are still intact moist tropical forest (Stone et al. 1994) and a coarse resolution sensor would be appropriate for a C flux estimate (Schroeder and Winjum 1995). Likewise, if mixtures of classes recognizable at a fine scale were generally repeated across the landscape (e.g., the areas of arctic tundra characterized by regularly spaced ice wedge polygons), then a coarse scale classification which recognized the mixtures might be acceptable. The most significant scale dependent errors could be expected where the disturbance regime creates large disparities in the C pools and flux across successional stages and the resolution of the satellite sensor is close to the scale of the disturbances. These observations generally suggest that as human land use becomes more intensive and extensive, the likelihood of scale dependent errors in C flux estimation with coarse resolution sensors may increase.

Although not within the scope of this study, quantitative assessment of error in the remote sensing-based measure and multiply approach could extend beyond the analysis of spatial resolution. Notably, there is always classification error in remote sensing-based land cover maps and corresponding error in C flux estimates (Riley et al. 1997). The magnitude of the classification error was evaluated in the original studies associated with the high resolution land cover map used in this study (Cohen et al. 1995). If a coarser resolution sensor were used over the same area, a similar error could be determined and compared with the error at high spatial resolution. Measurement error refers to the uncertainty associated with the measurement technique, e.g., the variability found in repeated measurement of biomass in the same plot. Measurement of carbon pools and flux, particularly in forests, is fraught with difficulties (Gower et al. 1999) and measurement error can be potentially large. Sampling error is a third source of uncertainty. The representative C flux values for the stand age classes were averages for medium productivity Douglas-fir forest covering the entire west side of the Cascade Range. That area of 36,000 km^2 (Powell et al. 1993) is large relative to the 98 km^2 subset examined in this study and the large area would have a mean value different from the mean value in any subarea. More generally, representative C pool estimates for particular cover types such as boreal forests may be biased towards high values because the plots on which the representative values are based are more likely to be robust examples (Botkin and Simpson 1990).

These errors propagate to determine the overall uncertainty of the C pool and flux estimates. When such estimates involve a chain of calculations, with variances associated with each term, first order Taylor series approximations of total error are sometimes used (Robinson 1989). However, correlation among error terms, excessive component variances, and other problems may invalidate that approach (Robinson 1989) and Monte Carlo simulation or other complex procedures may be required to address error propagation. In that regard, the difference approach for estimating carbon sequestration or loss (Kaupi 1992; Cohen et al. 1996), may be more sensitive than the measure and multiply approach to errors associated with coarsening of spatial resolution. The difference approach involves compounding two errors for the estimate of biomass. Each error would be on the order of 29% for the managed forest landscape in this study.

Generally, systematic approaches to error analysis in large area carbon flux estimates are only beginning to be made (e.g., Ciezewski et al. 1996, Phillips et al. in review) but issues associated with uncertainty will likely become increasingly important as these estimates become more tightly linked to development of policy related to climate change. The Kyoto Protocol (United Nations 1997) calls for generating and periodically updating national-level C budgets which indicate C flux associated with the land base. Remote sensing is an attractive option for this application because of its ability to do wall-to-wall coverage independent of ownership. However, it will be important to systematically assess associated errors, beginning with classification error itself and running through the additional considerations noted above.

Estimating C flux with spatially-distributed, process-based biogeochemistry models will also be subject to scale-dependent errors. Like the difference approach, the biogeochemistry models depend on vegetation cover maps to initialize carbon pools (e.g., McGuire et al. 1992). In addition, vegetation cover or functional type determines a set of physiological constants, such as maximum stomatal conductance, which are inputs to the model. As with the biomass values, there can be large differences in the physiological constants such that final errors associated with misclassification at coarse spatial resolution could be different than effects related only to proportional estimation errors. Effects of alternative spatial resolutions would also be manifest via influences on other initialization variables related to soil properties (Farajalla and Vieux 1995) and climatic input variables such as air temperature (White and Running 1994; Pierce and Running 1995; Turner et al. 1996).

The light use efficiency approach (LUE) to NPP estimation (Ruimy et al. 1994) may be somewhat less sensitive to coarsening of spatial resolution than the other NPP algorithms. In one variant of this approach (Prince and Goward 1996), the reference efficiency factor for gross primary production (gC MJ^{-1}) is a single value for all vegetation types. Thus, land cover classification is not an issue. The fraction of photosynthetically active radiation which is absorbed by the canopy (f_{APAR}), a critical component of the LUE algorithm, is nearly linearly related to the Normalized Difference Vegetation Index from satellite imagery (Sellers 1987). Analyses with radiation transfer models suggests that the f_{APAR}-NDVI relationship is to some degree independent of pixel heterogeneity (Myneni and Williams 1993), thus minimizing the impact of spatial resolution on NPP estimates. In other variants of the LUE approach, vegetation classification is used to assign a biome-specific LUE (Ruimy et al. 1994), so a sensitivity to errors in land cover classification associated with coarse spatial resolution is introduced.

Implications for validation of global C flux products

Continental to global scale maps of terrestrial NPP or NEP have been produced by a variety of means, most commonly by use of spatially-distributed biogeochemistry models (Potter et al. 1993; VEMAP 1996). These analyses have typically been carried out on grids of 0.5° of longitude × 0.5° of latitude, which represents cells about 50 km on a side in the temperate zone. As noted, the satellite-based global NPP estimates will also be at a coarse resolution relative to the scale of heterogeneity in land cover in some landscapes. At the hemisphere or global scale, there are prospects for validating these C flux estimates by inversion of 3-D atmospheric transport models coupled to observations of spatial and temporal patterns in the concentration of atmospheric CO_2 (Hunt et al. 1996). However, validation of flux estimates at the local level, as is explored in this study, is also needed for understanding of the mechanisms driving biospheric influences on the global C cycle (Running et al. 1999).

A key issue related to the local validation of large scale C flux maps has been the fundamental mismatch in spatial scale between the plots used to measure

NPP, e.g., 1 m^2 plots for grasslands and 1 ha plots for forests, and the dimensions of the grids used in global modeling. High resolution remote sensing offers a means of bridging that gap because the pixel size more nearly matches the NPP measurement plot size and the domain can extend to the size of a coarse resolution grid cell (Reich et al. 1999). Specific ongoing applications of high resolution remote sensing for validation purposes include the Global Primary Production Data Initiative (GPPDI) and the BigFoot project.

GPPDI is using the measure and multiply approach among other approaches for characterizing NPP over selected half degree by half degree cells in several biomes (Olson and Prince 1996). The BigFoot project is mapping land cover and NPP over 25 km^2 areas associated with eddy covariance flux towers for use in validating NPP surfaces from EOS/MODIS (Reich et al. 1999). These validation applications, in which high resolution remote sensing are an essential component of the C flux scaling algorithm, offer the opportunity to develop and test tools for screening samples of the Earth's surface with respect to their sensitivity to coarse resolution analysis. Metrics from the discipline of landscape ecology, such as the trends in proportional estimation error and local variance with coarsening of spatial resolution, could ultimately be used to stratify the Earth's surface in terms of the optimal spatial resolution for C flux monitoring.

Conclusions

Mapping of land cover using satellite remote sensing is a critical component of several approaches to scaling NPP and NEP to the landscape, regional, and global domains. A variety of current and planned satellite-borne sensors are potentially useful in these approaches, however, the differences among them in spatial resolution is an important consideration. For a managed forest landscape in the PNW region, a spatial resolution $\leq$ 250 m may be needed to capture the heterogeneity in land cover imposed by the human-dominated disturbance regime. This situation may become increasingly common globally as the impacts of human land use become more intensive and extensive. The various approaches to C flux estimation which depend on land cover maps differ in their sensitivity to scale-dependent mapping errors.

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