Forest biomass estimated from MODIS and FIA data in the Lake States: MN, WI and MI, USA

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Summary

This study linked the Moderate Resolution Imaging Spectrometer and USDA Forest Service, Forest Inventory and Analysis (FIA) data through empirical models established using high-resolution Landsat Enhanced Thematic Mapper Plus observations to estimate aboveground biomass (AGB) in three Lake States in the north-central USA. While means obtained from larger sample sizes in FIA datasets can be used as reference numbers over large scales, remote sensing (RS)-based observations have the ability to reflect spatial variation of properties of interest within a given area. Thus, combining two national on-going datasets may improve our ability to accurately estimate ecological properties across large scales. Using standard and consistent data sources can reduce uncertainty and provide more comparable results at both temporal and spatial dimensions. We estimated total forest AGB in the region was 1479 T_g (10^{12} g, dry weight) in 2001 with mean AGB value of 95 mg ha^{-1} ranging from 4 to 411 mg ha^{-1} (within 95 per cent percentiles). Mixed forests featured 66 per cent of the total AGB while deciduous and evergreen forests contained 32 and 2 per cent of the total AGB, respectively, at 1-km pixel resolution. Spatially, AGB values increased from north-west to south-east in general. The RS-based estimates indicated a greater range in AGB variations than the FIA data. Deciduous forests were more variable (both in absolute and relative terms) than evergreen forests. The standard deviation of AGB for deciduous forests was 137 mg ha^{-1}, or a coefficient of variation of 92 per cent, that for evergreen forests was 24 mg ha^{-1}, or a coefficient of variation of 37 per cent.

Introduction

Plants are the second largest reservoir of carbon storage in the terrestrial ecosystem and much of this reservoir is forest. Forests cover ~40 per cent of the ice-free land surface of the earth (52.4×10^6 km^2, Waring and Running, 1998). Accurately estimating different components of forest carbon storage (e.g. aboveground biomass (AGB)) over large scales can improve our understanding of forest carbon cycles and dynamics associated with land use and climate changes (Woodwell *et al.*, 1978; Adams *et al.*, 1990; Keeling *et al.*, 1996). AGB estimates are also useful information for other ecological studies such as fuel loading prediction, net primary production and soil carbon and nutrients accumulation (Clark *et al.*, 2001; Feldpausch *et al.*, 2004; Ryu *et al.*, 2006).

Various satellite metrics such as the normalized difference vegetation index (NDVI), enhanced vegetation index, land surface reflectance and other land cover characteristics from the NASA Moderate

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Resolution Imaging Spectrometer (MODIS) provide promising and reliable information for monitoring ecosystem properties and processes over large scales because of good spectral relationships between ground vegetation and remotely sensed information (Running *et al.*, 1989; Prince and Goward, 1995; Cohen *et al.*, 2002; Xiao *et al.*, 2004; Zheng *et al.*, 2004b). Ecological studies at regional scales using remote sensing (RS) techniques are an important step, and represent a necessary pathway, for scaling numerous existing plot-level observations of interest to address urgent and critical issues at national, continental or global scale, such as quantifying carbon storage and fluxes among different components of forest ecosystems and their relationships to climate fluctuation and change.

Combining satellite observations with natural resources field-collected inventory data (forest, grassland and cropland) for national and global carbon-related studies will provide more consistent, reliable and comparable analyses across both spatial and temporal dimensions. Overall, uncertainties can be reduced. In the USA, for example, the USDA Forest Service, Forest Inventory and Analysis (FIA) Programme has been using systematic sampling schemes for surveying forestlands across the nation with periodic updates since the early 1930s (Bechtold and Patterson, 2005). Using these field-collected inventory data, efforts have been made to provide generalized methodologies for forest biomass and carbon studies across the US (Pastor *et al.*, 1984; Birdsey, 1996; Jenkins *et al.*, 2004; Smith *et al.*, 2006). While the mean values of various interested ecological properties provide unbiased average conditions over a large area, RS-based estimates for the corresponding properties can illustrate how these ecological properties vary spatially compared with the means within the areas and by how much (Zheng *et al.*, 2004a). Therefore, appropriately linking ground-based national inventory data and RS-based observations can enhance the applications of ecological studies over large scales. Recent collaborations among NASA, FIA and other Forest Service and University partners indicate that potential benefits from linking the information have begun to be recognized by colleagues, scientific communities and governmental agencies (Healey *et al.*, 2005).

Many studies have demonstrated that RS techniques can be directly or indirectly used for estimating aboveground forest biomass at various scales (Sader *et al.*, 1989; Jakubauskas, 1996; Hame *et al.*, 1997; Lefsky *et al.*, 1999; Steininger, 2000; Sannier *et al.*, 2002; Zheng *et al.*, 2004b). However, directly linking MODIS data with FIA plot observations on the ground can be inappropriate and problematic because of a mismatch in spatial resolutions between the two data sources (Turner *et al.*, 2004). In contrast to the finest MODIS (pixel size at nadir) observations at 250-m resolution (NASA, 2005), FIA phase-2 permanent plots cover ~672 m^2 of area (Bechtold and Patterson, 2005). Therefore, a logical and practical alternative is to directly link the field plot observations with high-resolution Landsat (30 m) data (Turner *et al.*, 2004; Zheng *et al.*, 2004b), and then use 1-km MODIS data for model applications over large area after the spectral calibrations between the Landsat and MODIS have been conducted. High correlations within the similar spectral ranges between the sensors have been reported (Alexandridis and Chemin, 2002; Fang *et al.*, 2004).

This study will (1) demonstrate how MODIS reflectance data were used to estimate AGB by linking to empirical models developed from Landsat Enhanced Thematic Mapper Plus (ETM+) data in three Lake States; (2) reveal how the FIA data could be used for adjusting and evaluating the MODIS-based AGB estimates at the regional level and (3) examine the spatial pattern of AGB distributions in the region and the AGB distributions among general forest types.

Materials and methods

Study area

The study area covers ~155 650 km^2 of forests (32 per cent of the total land area) in three Lake States of USA: Michigan (MI), Minnesota (MN) and Wisconsin (WI) based on the MODIS land cover map of 2001. The region ranges from 41° N to 49° N in latitude and from 97° W to 83° W in longitude. Climate in the region is characterized by warm summers (mean from 14 to 15.5°C) and cold winters (mean = −13°C) with mean annual temperature ranging from 1 to 2°C. Mean annual precipitation ranges from 500 mm in the west to 700–800 mm in the east (Chaplin *et al.*, 2001).

Dominant forest species are aspen-birch (*Populus tremuloides, Betula papyrifera*), northern hardwoods (*Acer saccharum, Acer rubrum, Quercus rubra*) and a mixture of conifers (*Pinus banksiana, Pinus resinosa, Thuja occidentalis, Picea mariana, Abies balsamea*) (McWilliams *et al.*, 2000) extending from east of the prairie borderlands in MN, through northern WI, northern MI and the northern-most two-thirds of the southern MI peninsula (Carleton, 2003). Age structure data from the last three FIA survey cycles suggest that the region is still dominated by young forests with most stands between 30 and 60 years of age (Schulte *et al.*, 2003).

FIA data

FIA is a continuing programme mandated by Congress since early 1930s, according to the Forest and Rangeland Renewable Resources Planning Act of 1974 and the McSweeney–McNary Forest Research Act of 1928. FIA's primary objective is to determine the extent, condition, volume, growth and depletion of the Nation's timberland (Alerich *et al.*, 2005). Before 1999, all inventories were implemented by the regional offices periodically. With passage of the 1998 Farm Bill, Congress directed major changes in the way FIA conducts inventories, and prescribed an annual inventory where a proportion of plots (usually 20 per cent in the eastern US and 10 per cent in the western US) in each State must be measured every year. Such a switch from a variety of regional periodic surveys to a nationally standardized annual inventory could improve the data quality for long-term forest studies across the nation (Bechtold and Patterson, 2005).

The FIA plots, located in a systematic way across the nation's forestland with a sampling intensity of at least one plot per 24 km^2 but varying from state to state, provide unbiased estimates of areal means and totals. The general principles of design-unbiased inference from this type of systematic survey are given by Thompson (2002, ch. 12), while model-unbiased estimators specific to FIA data are given by Bechtold and Patterson (2005). There were a total of 21 685 plots used in this study with 10 220, 5074 and 6391 in MI, MN and WI, respectively. The mean sample error at the state level in the region was 0.7 per cent at the 67 per cent confidence level (one standard error) (USDA, Forest Service, 2006).

We used the FIA tree-level data in 2001 (MN) and 2002 (WI and MI, the closest year to 2001 that are available) for calculating AGB density (mg ha^{-1}, dry weight (DW)) because the high-resolution-based empirical models were built using the 2001 ETM+ scene. The AGB in this study is defined as all live trees with diameter breast height (d.b.h.) $\geq$ 2.5 cm including stem, branch and foliage (trees with TPACURR = 0 (current trees per acre) were excluded from calculations). Our calculation does not include understorey biomass estimation which may introduce additional uncertainty. However, understorey biomass only accounted for ~3.4 per cent of total AGB in the region ranging from 2.8 per cent in MI to 4.3 per cent in MN (Smith and Heath, in press).

AGB for each tree in a given plot was calculated as a function of d.b.h. based on 10 generalized regression models developed for all North American tree species (Jenkins *et al.*, 2004). Tree-level AGB was summed to plot-level and converted to mg ha^{-1}.

MODIS data

The first MODIS sensor was launched on 18 December 1999 (NASA, 2006b). MODIS is a 36-band spectrometer providing a global dataset every 1–2 days with a 16-day repeat cycle. This makes it possible to continuously monitor our environment and to map the surface of cloud, land and sea in a variety of spectral ranges from the blue to the thermal infrared (NASA, n.d.).

We downloaded two kinds of MODIS data for the study area from the Land Processes Distributed Active Archive Center (USGS-NASA, 2006): 1) surface reflectance (composite from 10 to 14 June 2001, MOD09A1, so the quality of image for the entire area is improved) in bands 1, 2 and 6 corresponding to spectral channels of red, near infrared and middle infrared, respectively; and 2) land cover map of 2001 (MOD12Q1, type 2 classification). The type 2 is one of the five classification systems in the MODIS land-cover map that has the identical forest types as those used in the 1992 global land-cover map generated by the University of Maryland, USA, based on Advanced Very High Resolution Radiometer data.

Therefore, this classification system provides the potential for land-cover change detection of forestlands between the 1990s (before MODIS was launched) and the 2000s. The reflectance data have spatial resolutions of 250 m for bands 1 and 2, and 500 m for band 6. The reflectance in both bands 1 and 2 has been resampled to 500 m resolution in the MODIS reflectance products for downloading. The reflectance data were used directly or indirectly for calculating various indices requested as model inputs. The land-cover map at 1-km spatial resolution was used for identifying forestlands in the study area. Five forest types derived from the MODIS land-cover map were aggregated to three broader classes in this study: 1) evergreen, 2) deciduous and 3) mixed forests. All MODIS reflectance data were resampled to 1-km resolution to match the land-cover map. Consequently, our simulated forest age map and AGB estimates were also at 1-km spatial resolution.

Empirical models

A previous study illustrated that AGB can be reasonably estimated for deciduous (de) and evergreen (ev) forests in the Chequamegon National Forest (CNF, covering ~440 km^2), WI using separate empirical models (Zheng *et al.*, 2004b). The models were developed based on field measurements and high-resolution (30 m) Landsat 7 ETM+ data (Figure 1) acquired on 12 June 2001, with high values of r^2. The models are

$$AGB_{ev} = 111 \times [NDVIc^{10.3}/(NDVIc^{10.3} + 0.35^{10.3})],\ r^2 = 0.86 \text{ and} \quad (1)$$

$$AGB_{de} = 233 \times NIR + 2.7 \times AGE - 71,\ r^2 = 0.95, \quad (2)$$

where NDVIc is corrected NDVI, calculated from NDVI × [1 − (mIR − mIR_{min})/(mIR_{max} − mIR_{min})] (Nemani *et al.*, 1993). mIR represents middle infrared band (centred at 1640 nm); NIR is reflectance in near infrared band. During the simulations, the model used for AGB_{de} was also applied to mixed forests that are in general dominated by deciduous trees in the region (Frelich, 2002; Zheng *et al.*, 2004b).

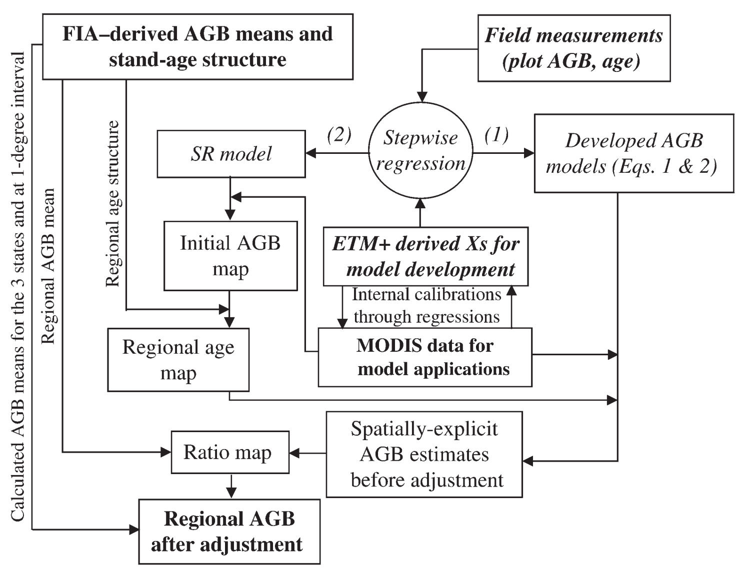

Figure 1. Flow chart of how MODIS data, with ancillary data from the USDA Forest Service FIA, were used for regional forest AGB estimates based on empirical modes resulting from Landsat data and ground observations. Rectangular boxes with bolded text are inputs and final output; the circle and other boxes are function and intermediate products. Steps in italic were completed in a previous study in Chequmegan National Forest, WI (Zheng *et al.*, 2004b).

Model application and evaluation

While high-resolution Landsat 7 ETM+ data were directly linked with field observations for establishing empirical models in CNF, MODIS data were used for model applications at regional scale. However, prior to regional application, spectral relationships in red, near infrared and middle infrared channels obtained from MODIS and Landsat 7 must be examined (Figure 1). Previous studies have indicated that such inter-comparison and calibrations between different sensors are necessary for terrestrial ecosystem studies (Lucht, 1998; Zhan *et al.*, 2002; Fang *et al.*, 2004). During the calibration, we first aggregated the 30-m Landsat reflectance (after atmospheric correction, NASA, 2006a) in the CNF area to the same resolution as the available MODIS reflectance data; second, we correlated the aggregated Landsat reflectance with the MODIS reflectance data within the CNF. The resulting regressions (Figure 2) were then applied to the study area for internal calibrations between the two sensors.

FIA-derived regional stand-age structure and AGB means (area weighted) at different levels were used for model application and evaluation as well (Figure 1). First, regional age structure was the base for determining the threshold values (Table 1) to convert initial biomass estimates to stand age whose overall distribution curve matched the one obtained from FIA data. Second, regional mean AGB was used as the reference number for adjusting satellite-derived AGB estimates through a ratio map. Third, FIA-derived AGB means at state level (n = 3) and at 1-degree interval on both latitudinal and longitudinal dimensions (n = 8 and 14, respectively) were used for comparing the means and standard deviations (SDs) between the satellite-based and FIA-based AGB estimates. We used ERDAS 8.7, Arc/Info 9.1 and Arc/View 3.3 for image processing, data analyses and spatial modelling.

Creating a regional age map and a ratio map

As indicated in equation (2), age is a major driving variable to estimate the AGB in hardwood and mixed forests (dominated by hardwoods). Therefore, a spatially explicit age map across the region is necessary for model application. To create such an age map, we first generated an initial biomass map estimated from the remotely sensed simple ratio (SR) of NIR/red (Figure 1). This index explained 51 per cent of variance (data not shown) and was not included in the AGB model. The initial biomass map was then overlaid by the land-cover map with an assumption that areas with higher biomass estimates indicate denser and older forest stands. We also assumed that an approximately linear relationship exists between age and biomass accumulation because of relatively young age structure in the region (Schulte *et al.*, 2003). In other words, AGB in most forests has probably not reached an expected asymptote (Jarvis and Leverenz, 1984). The threshold values (Table 1) used for dividing general age classes (young, intermediate and old) were carefully determined after simulations repeated in such a way that the simulated age structure matched the regional structure obtained from FIA plot data (Schulte *et al.*, 2003). The age values within the general age classes were linearly interpolated based on biomass values. The created age map, together with the NDVIc, and NIR maps derived from the MODIS (after internal spectral calibrations) were the inputs for producing a final biomass map of the region using equation (1) or (2) depending on forest type. The age variable resulting from SR and further constrained by the regional age structure obtained from the FIA data was poorly correlated to NIR in equation (2) (r^2 = 0.081) across the region.

The final biomass estimates were further converted to a ratio map to show how AGB varied spatially across the region compared with its mean (Zheng *et al.*, 2004a) by dividing the AGB value in each pixel by the mean AGB of all pixels within the area of interest (AGB_{pixel}/AGB_{mean}, Figure 3). As a result, this ratio map preserved the integrity of spatial variation of regional AGB detected by the satellite. We then multiplied the ratio map by the regional mean biomass value calculated from the FIA data to obtain the adjusted biomass estimates for the study area (Figure 1).

Results and discussion

Spectral relationships and the AGB estimates

Good relationships were found in red, near infrared and middle infrared channels, with r values

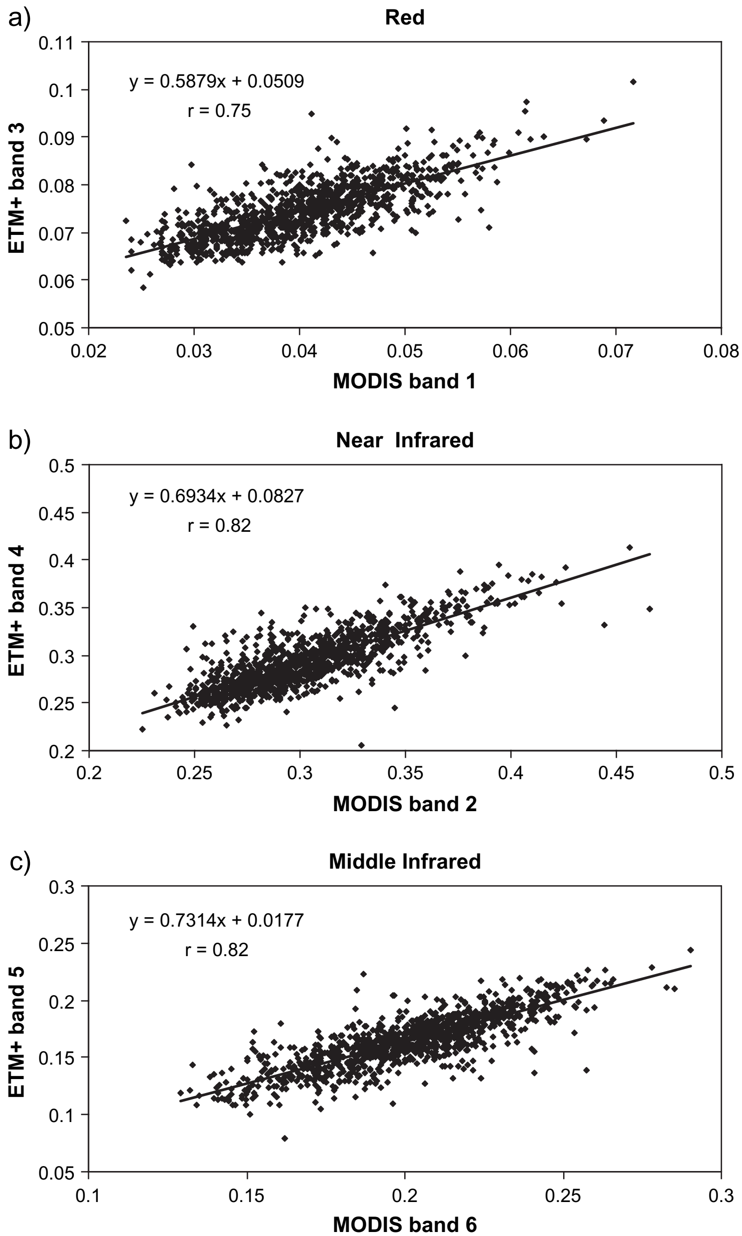

Figure 2. Spectral relationships in red (a), near infrared (b) and middle infrared (c, centred at 1640 nm) channels between the MODIS and Landsat 7 sensors after eliminating the scale (spatial resolution) effect. The empirical biomass models established using high-resolution Landsat data were applied to the entire region using MODIS reflectance data as inputs after internal spectral calibrations between the two sensors were conducted.

Table 1: The threshold values used for generating explicit regional forest age map of 2001 in Tri-Lake states based on satellite-derived initial AGB (mg ha−1), land-cover map 0f 2001 from MODIS and the forest age structure obtained from the FIA data (Schulte *et al.*, 2003)

Cover types	Young (1–30 years)	Intermediate (31–65 years)	Mature (>65 years)
Softwood	0–40 mg ha^{-1}	41–105 mg ha^{-1}	>105 mg ha^{-1}
Hardwood	0–70 mg ha^{-1}	71–125 mg ha^{-1}	>125 mg ha^{-1}

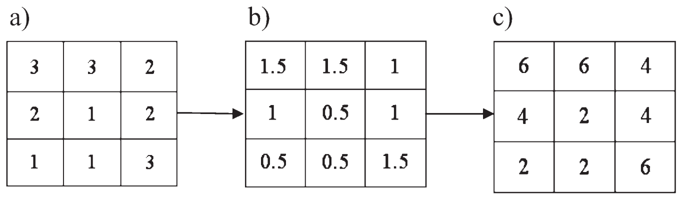

Figure 3. RS-derived AGB density (mg ha−1) was spatially adjusted by multiplying the FIA-derived mean AGB density through a ratio map across the region. In this example, for a 3 × 3 window: (1) the mean AGB density estimated from RS (a) can be calculated (e.g. = 2); (2) the ratio map (b) can be developed (AGB_{pixel}/ AGB_{mean}) and (3) assuming the mean AGB density calculated from FIA plots within the 3 × 3 window was 4, the adjusted AGB map (c) was obtained (e.g. ratio map × 4).

of 0.75, 0.82 and 0.82, respectively, between the MODIS and Landsat sensors (Figure 2). These relationships provided justification for applying MODIS data for regional AGB estimates based on locally established empirical models.

Total aboveground forest biomass in the three Lake States was 1479 T_g (10^{12} g, DW) in 2001 with mean AGB of 95 mg ha^{-1} (SD = 95 mg ha^{-1}) ranging from 4 to 411 mg ha^{-1} within 95 per cent percentiles, using MODIS products (e.g. reflectance and land-cover map) as inputs. The results compared well with a previous report that the projected upper limit of AGB for mature forests in northern WI was 600 mg ha^{-1} (Crow, 1978). Additionally, Crow (1978) reported AGB for three contiguous hardwood stands in northern WI ranged from 94 to 119 mg ha^{-1}.

Mean AGB values increased from 74 mg ha^{-1} in MN, 103 mg ha^{-1} in WI, to 111 mg ha^{-1} in MI (Table 2) partly because a similar pattern existed for old growth (>100 years) composition, increasing from ~5 per cent in MN, 7 per cent in WI, to 12 per cent in MI (Schulte *et al.*, 2003). The differences between our RS-derived and FIA-derived biomass estimates were −6.1, 6.1 and 1.5 per cent for MN, WI, and MI, respectively (Table 2). Our estimated mean AGB values at the state level were also comparable with those reported in the USDA forest greenhouse gas inventory for 1990–2005 (Smith and Heath, in press). Our resulting AGB means were lower than the reported number (Table 2), mainly because in our calculations both forest and non-forest portions of the plots were included, which was closer to what RS could 'see'; the field-collected forest inventory data calculated only the forest portions of the plots. Furthermore, our estimates do not include understorey and root carbon.

In all cases, RS-based AGB estimates showed higher spatial variation (SD) than FIA-based estimates (Table 2), which could be an indication of improving our current understanding of how AGB was spatially distributed across the region. Our RS-based estimates include 'all' forest conditions while FIA inventories typically have been conducted on productive timberland but not on other forestlands, not on reserved forestlands, and depending on the region, not on National Forest System lands (Bechtold and Patterson, 2005). For example, some conditions (such as very low productivity and highly fragmented forestlands) are excluded from FIA data based on definition of timberland. Our estimates include these forestlands.

Table 2: Comparison between the adjusted remote sensing (ARS)-derived AGB, mg ha−1) and FIA-derived AGB estimates in 2001 at state level

	Mean			SD	
State (1000 ha)*	USDA†	FIA	ARS	FIA	ARS
MN (4841)	89	78	74	55	64
WI (4934)	111	97	103	62	108
MI (5781)	123	109	111	69	107
Entire (15 565)		95	95	66	95

* Forestlands only based on the 2001 MODIS land-cover map.
† USDA green gas inventory 1990–2005 (Smith and Heath, in press).

AGB distribution, frequency analyses and storage by forest types

Spatially, high AGB values occurred in lake shore areas of Lake Superior and less-disturbed National Forests or conservation areas scattered across the region, while low AGB values were observed in north-west and north-central areas of MN as well as north-eastern WI and adjacent areas of the Upper Peninsula of MI (Figure 4a), where young or less-dense forests existed (Figure 4b). About 84 per cent of forestlands had ages ≤60 years old, with forestland of age greater than 90 years old accounting for 9 per cent (Figure 4b). As a result, the modal class of AGB occurred between 41 and 80 mg ha^{-1} (32 per cent), followed by 81–120 mg ha^{-1} class (25 per cent). Forest biomass density > 200 mg ha^{-1} comprised 8 per cent of forestland (Figure 4a).

Frequency distribution of the RS-derived AGB estimates followed a somewhat bimodal shape (Figure 5a) basically because of a similar distribution shape for forest age structure (Figure 5c). Bimodality of the distribution is statistically significant, using dip test of Hartigan and Hartigan (1985) (dip statistic = 0.0054, $P < 0.01$). High occurrence of AGB value 1 was caused by operational control during the simulation and for effective presentation of the results. The impact of assigning pixels with the estimated biomass values <0 as 1 should be minimal for overall analyses in terms of AGB amount and spatial variation because those places were more likely to have low biomass and accounted for only a small portion of the study area (1.3 per cent). Frequency analysis for our reconstructed regional forest age map (Figure 5c) well-matched the general age structure reported by Schulte *et al.* (2003). Their study indicated that forests with age <30 years accounted for ~40 per cent of forestland; forests >90 years old was 8 per cent; most stands were between 30 and 60 years of age with the remaining forests between 60 and 90 years of age in the three states. Our estimated frequencies for the corresponding age categories were 39.6, 8.5 and 44.8 per cent, respectively. Comparison of frequency distributions between RS- and FIA-based AGB estimates (Figure 5a,b) indicated that the FIA plot data collected at a much smaller spatial scale (<<1 ha) than the MODIS biomass estimates (1 km^2) are more variable than MODIS data collected within the same forests. Taken together, the two processes (truncation of extreme forests in the FIA data, and differences in sampling scale) account for the result that the MODIS data have a greater range but a more concentrated frequency distribution within 30–80 mg ha^{-1} range of AGB (Figure 5a) than that of the FIA data (Figure 5b).

Our results suggested that, by cover types, deciduous forests had the highest mean biomass (149 mg ha^{-1}), containing 32 per cent of total forest AGB in the region. Mixed forests (mean AGB of 83 mg ha^{-1}) with 76 per cent occurrence in the region accumulated 66 per cent of the total AGB. Evergreen forests contained small portions of the regional AGB (2 per cent) because of both (1) the smallest AGB mean value (65 mg ha^{-1}) and (2) the smallest percentage of land area present (3 per cent) based on the 2001 MODIS land-cover map at 1-km resolution (Figure 6). Deciduous forests were more variable (both in absolute and relative terms) than evergreen forests. The SD of AGB for deciduous forests was 137 mg ha^{-1} (or a coefficient of variation of 92 per cent); while that for evergreen forests was 24 mg ha^{-1} (or a coefficient of variation of 37 per cent, Figure 6).

Evaluating RS-based and FIA-based AGB estimates

Further comparisons between RS-based and FIA-based AGB estimates at latitudinal and longitudinal dimensions (with 1-degree interval) showed

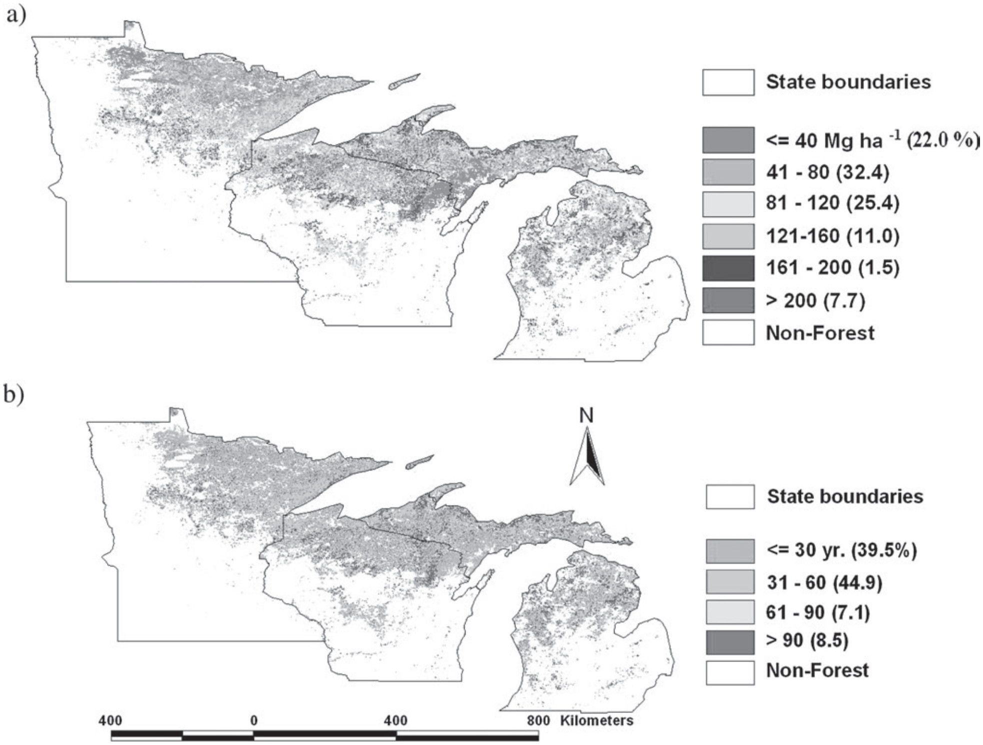

Figure 4. RS-derived forest biomass map adjusted using FIA-derived regional mean AGB (a) and forest age map (b). Values in both maps were grouped into broader categories for better visualization. Numbers in parentheses are frequencies in % for given classes.

clear patterns of increasing AGB values from west to east and from north to south with much greater AGB gradients in the RS-based estimates than that in the FIA-based estimates (Figure 7a,c). These trends match the general climatic gradients in the region that precipitation across the region increases from west to east and temperature increases from north to south. In addition, considerable young or less-dense forestlands detected by the RS data in north-central and north-west MN belong to the transition area from east prairie to northern hardwood-conifer zone (Carleton, 2003), and this could also contribute to and reinforce the patterns we found. In this area, the coarse 1-km MODIS data may be including areas of prairie or cropland within heavily forested pixels, which would not have been mapped as forestland by FIA.

The RS-based methodology seems to 'amplify' the AGB contrast throughout the region by 'underestimating' the AGB at the places that are likely to have low AGB values while 'overestimating' the AGB at the places with high AGB values. Thus, the differences between the RS-based and FIA-based estimates can be quantitatively identified on both latitudinal and longitudinal dimensions with high correlations (Figure 7b,d) that could be used for future correction if necessary. The differences can be viewed either as improvements due to incorporating the RS technique or as errors. If it is the latter, the possible 'error' sources for this study were (1) FIA datasets (e.g. limited representation of extreme conditions), (2) RS datasets (e.g. land-cover map) and (3) modelling procedures, such as reconstruction of regional age map or the locally developed empirical models not providing the best fit for the entire region. No matter whether the differences are viewed as errors or improvements, the ability to detect systematic differences in

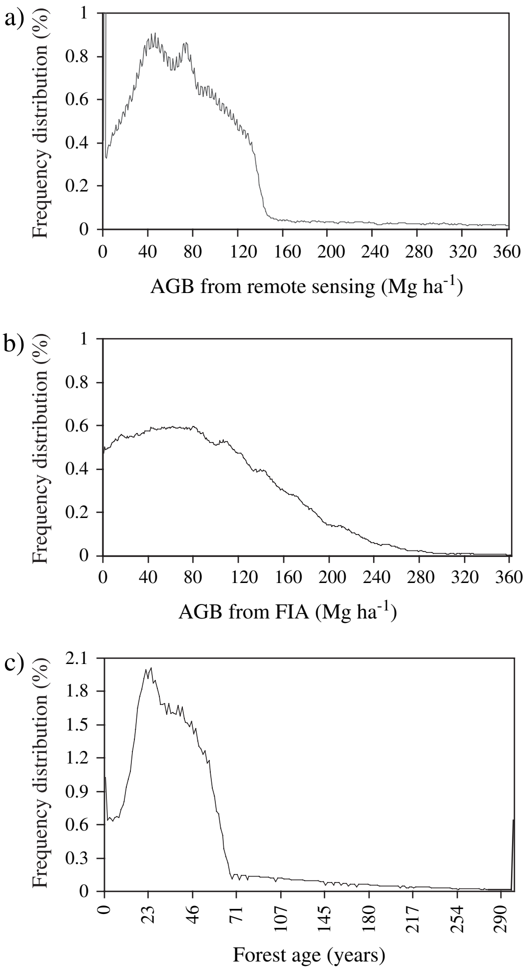

Figure 5. Frequency distributions of AGB (mg ha−1) in the three Lake States: (a) RS-based estimates of AGB after adjustment. High occurrence of the AGB value of 1 was due to all pixels with estimated biomass <0 (up to −50 mg ha−1) were assigned as 1; (b) FIA-based AGB calculation. In both (a) and (b), the AGB values were cut off at 360 mg ha−1to keep the axis identical and both curves were smoothed using a running average to show general pattern and (c) simulated forest age map based on the age structure resulted from FIA 2000 survey (Schulte *et al*., 2003).

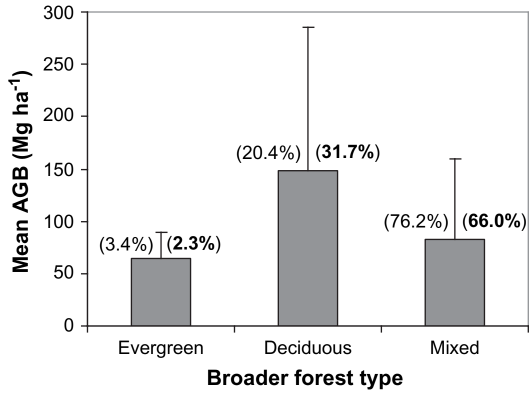

Figure 6. AGB (mg ha−1) and distributions by general forest types defined in the MODIS land-cover map (type 2 classification). Bars represent one SD. Numbers in the parentheses indicate the percentage of a given type to the total area (left side of the bars) and the percentage of total AGB by the type compared with the region's total AGB (right side of the bars in bold).

AGB estimates is an encouraging step forward. The pattern of systematic errors can be used to develop testable hypotheses that can be fruitful areas for further study. Furthermore, systematic errors associated with known covariates can be corrected by sampling (e.g. ratio or regression sampling (Thompson, 2002) or through iterative improvement of the model). For example, higher SD in RS-based estimates can be reduced by lowering the maximum age that was used in the simulations (currently all pixels with ages >300 years (0.6 per cent) were truncated to 300) or by modifying the age structure. However, more similar case studies using FIA and MODIS data on AGB estimates in other regions across the country are needed to see whether similar patterns exist elsewhere.

While AGB means are useful for comparison purposes, total biomass estimates across the entire region may be more important to decision makers. However, we should evaluate total biomass estimates (rather than per unit density estimates) with caution, because the estimates of forest areas over large scales can differ substantially among various conventional cartographic sources (Townshend *et al*., 1991; S.W. Running, personal communication), and this affects the calculation of total biomass. From this perspective, RS-based land-cover maps using the same classification criteria can provide consistent and comparable AGB estimates in both temporal and spatial dimensions over large scales.

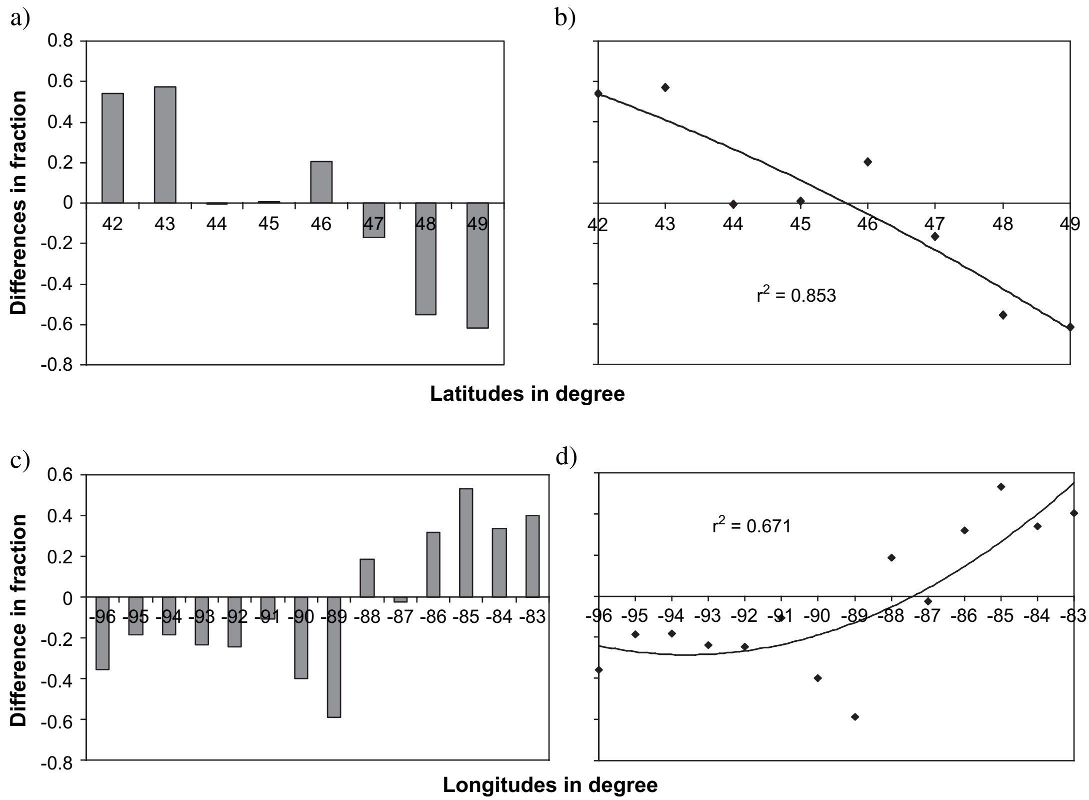

Figure 7. Spatial patterns of differences between FIA-based and RS-based AGB (mg ha−1) estimates examined in both S-N and W-E dimensions with 1-degree interval across the region (a and c). The fraction was calculated as (AGB_{rs}/AGB_{fia} − 1). Both latitudinal and longitudinal degrees represent the upper boundary (e.g. 42 = 41 − 42° N, etc.). The patterns can be well quantified using the best fits (b and d).

Conclusions

While MODIS products are a promising and valuable data source for terrestrial ecosystem studies over large scales, spectral calibrations between MODIS and Landsat are needed before high-resolution-derived empirical models can be extrapolated to large areas with ecological environments similar to those where the models were developed.

Mean values of ecological properties developed from national inventory data with large sampling sizes can be used as reference numbers to further adjust RS-based estimates. Combining natural resources inventory data, such as FIA, and MODIS observations has the following advantages for forest carbon studies at regional and national scales by (1) providing standard and consistent data sources for more meaningful temporal and spatial comparisons and (2) reducing uncertainties in the error estimates. Systematic errors detected from using standard and consistent datasets can be useful for future correction if necessary.

Grid-based products like the AGB and age maps of 2001 generated from this study can provide baseline information for future comparisons and analyses on both temporal and spatial dimensions over large scales and are valuable resources for ecological studies on other related issues. More regional studies on this topic are needed to determine error patterns and testing the hypothesis whether a generalized methodology can be developed at the national level, or if specified regional models are needed which would be joined for a national result.

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Conflict of Interest Statement

None declared.

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