Landscape Ecol (2009) 24:1299–1313
DOI 10.1007/s10980-009-9379-z

RESEARCH ARTICLE

Scale dependence in quantification of land-cover and biomass change over Siberian boreal forest landscapes

**Tingting Zhao · Kathleen M. Bergen ·
Daniel G. Brown · Herman H. Shugart**

Received: 24 July 2008 / Accepted: 8 June 2009 / Published online: 25 June 2009

Abstract We investigated the influence of remote sensing spatial resolution on estimates of characteristic land-cover change (LCC) and LCC-related above-ground biomass change (Δbiomass) in three study sites representative of the East Siberian boreal forest. Data included LCC estimated using an existing Landsat-derived land-cover dataset for 1990 and 2000, and above-ground standing biomass stocks simulated by the FAREAST forest succession model and applied on a pixel basis. At the base 60 m resolution, several landscape pattern metrics were derived to describe the characteristic LCC types. LCC data were progressively degraded to 240, 480, and 960 m. LCC proportions and Δbiomass were derived at each of the coarser resolutions and scale dependences of LCC and Δbiomass were analyzed. Compared to the base 60 m resolution, the Logged LCC type was highly scale dependent and was consistently underestimated at coarser resolutions. The Burned type was under- or over-estimated depending strongly on its patch size. Estimated at the base 60 m resolution, modeled biomass increased in two sites (i.e., 3.0 and 6.4 Mg C ha^{-1} for the Tomsk and Krasnoyarsk sites, respectively) and declined slightly in one site (i.e., −0.5 Mg C ha^{-1} for the Irkutsk site) between the two dates. At the degraded resolutions, the estimated Δbiomass increased to 3.3 and 7.0 Mg C ha^{-1} for the Tomsk and Krasnoyarsk sites, while it declined to −0.8 Mg C ha^{-1} for the Irkutsk site. Results indicate that LCC and Δbiomass values may be progressively amplified in either direction as resolution is degraded, depending on the mean patch size (MPS) of disturbances, and that the error of LCC and Δbiomass estimates also increases at coarser resolutions.

Keywords Scale · Resolution · Land-cover change · Biomass · Disturbance · Forest succession · FAREAST model

T. Zhao · K. M. Bergen (✉) · D. G. Brown
School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48019, USA
e-mail: kbergen@umich.edu

Present Address:
T. Zhao
Department of Geography, Florida State University, Tallahassee, FL 32306, USA

H. H. Shugart
Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904, USA

Introduction

There is growing consensus that one of the key sources of continued uncertainty in regional-extent carbon assessments for many parts of the globe is the inconclusive measurement of land-cover change (LCC) resulting from both natural and human-driven disturbance and recovery (Hassan et al. 2005). Data on LCC are especially difficult to compile using conventional forest inventory or monitoring methods over large and remote boreal forest regions such as those of Northern Eurasia (Krankina et al. 2005a), and thus remote sensing facilitates data collection and analysis of LCC over these large geographic areas over time. Within the land-cover change community, data from the moderate spatial resolution sensors such as the Landsat series at 60 and 30 m have become a baseline for scaling land cover observations at coarser spatial resolutions (Steyaert et al. 1997). However, these moderate-resolution data are limited by small imaged area and coarse temporal resolutions. Data collected at coarser spatial resolutions (i.e. AVHRR or SPOT-VEGETATION at 1 km and MODIS or MERIS at 250 m to 1 km) are advantageous for timely measurement of regional-scale LCC, given large swath dimensions and frequent repeat collection. However, to what extent these coarse spatial resolution sensors may accurately estimate LCC of varying spatial size and configuration remains an open question.

Because the spatial resolution of most affordable continuous satellite data employed over the extensive Siberian region of the Northern Eurasian boreal forest is generally at 250 m or coarser, the potential exists for a bias in LCC inventories from the loss of spatial detail. Whether or how much of a bias exists in remotely sensed data of any scale depends on the relative spatial heterogeneity of LCC dynamics that are characteristic of the region (Strahler et al. 1986; Alpin 2006). Studies specifically investigating LCC heterogeneities and scaling relationships for Siberian boreal forests are lacking. Therefore the goal of our study, within the context of landscape-to-regional land change science, was to examine the effect of progressively degraded resolutions of satellite imagery on quantification of LCC and LCC-related above-ground biomass change (Δbiomass) at representative sites in the East Siberian boreal forest. The specific objectives were to (1) quantify representative East Siberian boreal forest LCC and spatial heterogeneity at a base moderate spatial resolution (60 m); (2) evaluate uncertainties of satellite imagery–based classifications of LCC at coarse spatial resolutions (i.e., 240, 480, and 960 m); and (3) explore the influence of spatial scale on estimates of Δbiomass at the same degraded spatial resolutions. To accomplish these objectives, we used progressively degraded Landsat-derived LCC data combined with modeled above-ground biomass data applied on a per-pixel basis. The simulated results given here provide a first approximation of the influence of spatial resolution in estimating LCC and Δbiomass in East Siberian boreal forests.

Background

LCC in Siberia

The dominant ecosystem in the East Siberian region of study is boreal taiga, with minor incursions of temperate–broadleaved and forest–steppe ecosystems (Olson et al. 2001). Major forest types are dark–coniferous forest of Siberian pine (*Pinus sibirica* Du Tour), Siberian spruce (*Picea obovata* Ledeb.), and Siberian fir (*Abies sibirica* Ledeb.); light–coniferous forest dominated by Scots pine (*Pinus sylvestris* L.) and larch (*Larix sibirica* Ledeb., *Larix gmelinii* (Rupr.) Rupr.); broadleaved deciduous forest of European White birch (*Betula pendula* Roth) and Upright European aspen (*Populus tremula* L.); and mixed coniferous–deciduous forest (Alexeyev and Birdsey 1998). Larch is somewhat more dominant in the mixed forests of the eastern reaches (i.e., Irkutsk Oblast).

LCC consists primarily of logging, fire, insect damage, agricultural conversion and abandonment, and forest regrowth and succession (Ranson et al. 2003; Bergen et al. 2008). Logging has historically occurred most often as clear-cuts in conifer and mixed forests. Fires also occur largely in conifer and mixed forests, and range in severity and size from small light surface fires to large stand-replacing crown fires (Conard and Ivanova 1997). The Siberian silkmoth (*Dendrolimus superans sibiricus* Tschetw.) is one of the principal causes of disturbance in conifer forests. The silkmoth caterpillars feed upon the needles of Siberian fir and pine (which are the preferred host species) as well as spruce; host species also include larch and, at the peak of outbreak, Scots pine. The outbreaks of this pest are especially harmful in the dark–coniferous forest type (Kharuk et al. 2004, 2007) Following stand-replacing disturbance, young forests grow on the disturbed sites. The most typical successional pathway is from young birch-aspen regeneration, through maturing deciduous forests, to mixed and conifer forest (Hytteborn et al. 2005). Disturbed larch and Scots pine-dominated forests, especially those on more extreme sites, often regenerate directly to these coniferous species. Abandonment of collective agriculture fields and subsequent colonization by young trees is a contributing factor to forest regrowth in the region (Krankina et al. 2005b).

Remote sensing and scaling

The potentially significant trade-offs between coarse spatial resolution but frequent wide-area coverage and moderate spatial resolution but limited coverage are persistent in remote sensing applications, and research on spatial scaling issues in remote sensing dates back to the 1980s (Strahler et al. 1986; Atkinson and Curran 1997; Alpin 2006). Several methods have been employed to analyze the effects of spatial scale, including comparing spectral images of different resolutions (Nelson and Holben 1986) as well as more complex approaches that include degrading remote sensing-derived land-cover classification data (also referred to as aggregating data) to coarser resolutions (Woodcock and Strahler 1987; Justice et al. 1989) and geostatistical techniques (Woodcock and Strahler 1987; Atkinson and Curran 1997).

Several studies have demonstrated the effectiveness of the Landsat sensors in capturing boreal LCC, producing carbon estimates in agreement with field-based inventories, and evaluating implications of scaling on land-cover maps. Landsat ETM+ 30 m data were used to accurately map logging, fire scars and insect damage in East Siberia (Ranson et al. 2003). In a study in Northwestern Russia, biomass derived from 30 m Landsat TM agreed well with data from forest inventories in terms of estimates of carbon (Krankina et al. 2004). A comparison between Landsat 30 m TM and 1 km AVHRR in boreal Canada showed that, where AVHRR 1 km pixels were resampled to Landsat TM 30 m pixels and then compared to a Landsat TM classification, most of the difference in land-cover class assignment was due to differences in the spatial resolution of the datasets (Steyaert et al. 1997), with significant loss of land-cover types with characteristically small patch sizes.

With respect to the influence of scale on carbon estimates, researchers in a Pacific Northwest forest found that estimates of net primary production (NPP) and net ecosystem production (NEP) decreased when calculated using input land-cover classifications at progressively degraded spatial resolutions from 25 m to 1 km, due to the increasing proportion of old-growth forests at the degraded resolutions (Turner et al. 2000). A study in the Russian Federation documented that over one-third of burn scars were smaller than 1,000 ha, and that failure to record these small burn scars in the multi–temporal 1 km SPOT VEGETATION dataset resulted in a 10% reduction of the estimated carbon emission from fires (Zhang et al. 2003). Research on effects of degraded land-cover data on estimating NPP within the US northern temperate-boreal ecotone showed a 7% increase in estimated NPP between 15 m and 1 km data, and 50% of the difference was attributed to the respective input land-cover data used with the light use efficiency (LUE) modeling method (Ahl et al. 2005). In general, studies over large northern forested landscapes have found different results in terms of direction (over- or under-estimation) and magnitude of scaling effects on carbon estimates. A plausible explanation for differences among such studies and one that we explore here is that spatial landscape characteristics of the regions under investigation influence the effects of scale on LCC and carbon-related estimates.

Study area

The study area included three case study sites in East Siberia, each covering the footprint of a Landsat scene and situated at similar latitudes (53–57°N) (Fig. 1). In this region, the climate is continental with long, severe winters and short, warm summers. The westernmost Tomsk site is on the ecotone between the West Siberian lowlands and Central Siberian plateau. The site has minor topographic relief with elevation ranging from ~100–200 m above sea level (asl) (USGS 1996), and is bisected by tributaries of the Ob River. A forest-agriculture landscape is interspersed with small settlements in the southern part of the site. The remainder of the site is primarily forest. Several patches of mature (dark) conifer still exist within a mosaic of secondary successional forests (birch-aspen or mixed forest) and disturbance patches. Logging observed at the second (1999) date is present in small rectangular patches (clear-cuts) following new prescribed size limits (Yaroshenko et al. 2001); prior to the mid-1990s logging typically occurred in larger landscape-sized and irregular-shaped clear-cuts. No new burns were observed at the second date in this site.

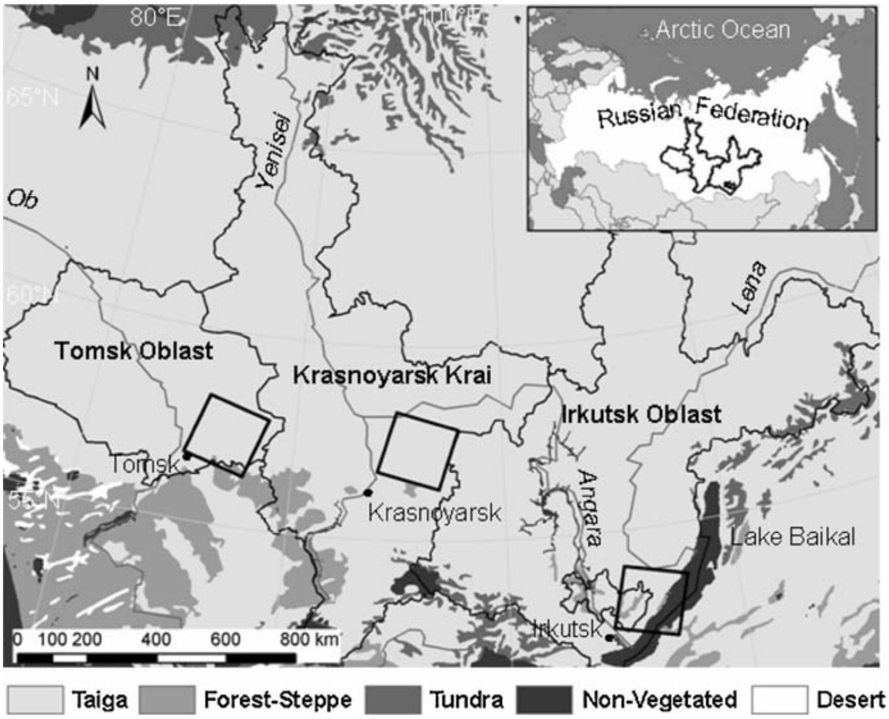


Fig. 1 Three case study sites (*black box outlines*) were sampled from Tomsk Oblast, Krasnoyarsk Krai and Irkutsk Oblast (*black administrative unit outlines*), centered at approximately 57.3°N/86.6°E, 57.3°N/96.1°E and 53.4°N/106.1°E, respectively. Map of potential vegetation cover is from Olson et al. (2001)

The Krasnoyarsk site lies on the Central Siberian plateau, an area of relatively minor topographic relief. The site is bisected by tributaries of the Angara-Yenisei River system. Agricultural areas are located in the southern third of the site and a portion of these areas are regrowing to young forest. In the northern two-thirds of the site, patches of mature dark coniferous forest remain within a mosaic of birch-aspen and mixed secondary successional forest and disturbance patches. The Krasnoyarsk site is fairly similar to Tomsk in its configurations of active and past logging. A small amount of fire (<1% by area) occurred in the site in the second (2000) date. Significant insect infestation (>6% by area) occurred in conifer and mixed forests before the second image date (1994–1996).

The easternmost Irkutsk study site contains a portion of Lake Baikal and has the greatest topographic relief, ranging from ~500 m above sea level at the Lake Baikal surface to ~2,055 m asl north and west of Lake Baikal. Several bare rocky areas occur along the western shore of Lake Baikal. Relatively dry forested uplands occur to the west of Lake Baikal, and logging and fires were concentrated in this area in the second (2001) study date (Peterson et al. 2009). Fires in the Irkutsk site were large and comprised 2.5% of the landscape at the second date. Further to the northwest, the somewhat dissected physiography supports primarily conifer or mixed (with larch) forests on drier slopes, and bogs and other wetlands in valley bottoms. A south central area is comprised of agricultural lands and small settlements.

Data

Land-cover data

We used an existing land-cover classification dataset that was based on Thematic Mapper (TM) and enhanced Thematic Mapper (ETM+) images taken during 1990 and 2000 and that had been processed and classified at a consistent thematic and spatial (60 m) resolution (Bergen et al. 2008). Twelve classes were represented in these data: Conifer, Mixed, Deciduous, and Young forests; Cut, Burn, and Insect disturbances; and Agriculture, Urban, Bare, Wetland, and Water land covers. For the disturbance categories, Cut referred to clear-cut areas, Burn identified severe stand-replacing fires, and Insect identified areas of mixed live and killed trees. Except for Water and Wetland (non-forested) that were excluded given their

Table 1 Summary of accuracy statistics for the land-cover and LCC data used in the present study

	Tomsk		Krasnoyarsk		Irkutsk	
Year	*1990*	*1999*	*1990*	*2000*	*1989*	*2001*
Overall classification accuracy	94.2	93.7	91.0	92.1	89.3	88.6
Period	*1990–1999*		*1990–2000*		*1989–2001*	
Estimated overall change accuracy	88.3		83.8		79.1	
Error/Noise proportion	4.52		4.82		13.73	

observed stability and the focus of the study on forest-related biomass changes, all mapped classes were retained for further analysis in the present study. The land-cover data classification and estimated change analysis accuracy statistics were obtained (Table 1).

Simulated coarse-resolution land-cover data

To estimate land-cover characteristics at degraded resolutions, the existing 60 m land-cover data were aggregated to resolutions of 240, 480 and 960 m. These degraded resolutions were selected as intuitively meaningful, being similar in spatial resolutions to commonly used 250, 500 m and 1 km remotely sensed data. Multiples of the base 60 m pixel size were used in order to avoid additional resampling. During the degradation process a decision rule was needed to assign a land-cover category to the new larger pixel. Because land-cover data are discrete and nominal, a moving window simple majority is often used for aggregation. When using continuous spectral data, a point spread function (PSF) (Huang et al. 2002) simulating spatial variation of spectral inputs at a finer resolution in a coarse pixel, can be applied in the procedure of resolution degradation.

We modified these approaches, using a moving window weighted aggregation scheme that simulates a PSF by approximating a Gaussian distribution in two–dimensional space and weighting all 60 m pixels located within each degraded pixel (i.e., the pixel block of 240, 480 or 960 m by size) with a total weight of 0.68, and those in the surrounding eight pixel blocks with total weights of 0.04 each. We compared the proportion of land-cover change categories in each degraded pixel derived with the simulated PSF approach against those from a simple majority filter for the Krasnoyarsk site. Results showed that the differences were very small across the different categories (mean 0.18%; range 0.03–0.58%), although the majority filter approach tended toward slightly higher proportions of small patch-size categories at the degraded resolutions and slightly lower proportions of the large-sized categories. We selected the PSF approach as it may more realistically represent the effects of spatial resolution change on land-cover data that is derived directly from spectral information collected by satellite sensors.

LCC data

At each spatial resolution of interest (i.e., 60, 240, 480 or 960 m), pixels were assigned to a change category based on observed changes between the ten land–cover classes in 1990 and those in 2000. There were 100 possible change classes, but most of the combinations did not occur. Many were functionally similar and therefore change classes were grouped into nine meaningful LCC types:

1. LOGGED: Forest in 1990 cut at or shortly before the 2000 image date with minimal or no regeneration to forest.
2. BURNED: Forest in 1990 severely burned at or shortly before the 2000 image date, minimally regenerated to forest.
3. INFESTED: conifer or mixed forest in 1990 damaged or killed prior to 2000 due to insect infestation in 1994–1996.
4. DEVELOPED: Forest in 1990 converted to agriculture or urban land in 2000.
5. REGEN I: Young forest regeneration after disturbance or from agricultural abandonment occurring between 1990 and 2000 (e.g., Conifer forest in 1990 observed as Young in 2000 due to fire or cut between 1990 and 2000).
6. REGEN II: Young following disturbances identified directly on the 1990 image.
7. SUCCESSION: Undergoing the process of succession (i.e. Young in 1990, Deciduous or Mixed forest in 2000).

8. Constant: Areas of no change in category between 1990 and 2000.
9. Unknown: Any change not included in the above (likely classification error).

All LCC types were present in the Krasnoyarsk site, all but Infested were present in the Irkutsk site, and all but Infested and Burned were present in the Tomsk site.

The nine LCC types were divided into four groups: Forest Disturbance, Forest Regrowth, Constant, and Unknown. This was done to couple the analysis of LCC types with the different trajectories of modeled above-ground forest biomass change (Δbiomass) between 1990 and 2000. Forest Disturbance is defined as any LCC type resulting in the net loss of forest biomass. This includes Logged, Burned, Infested, Developed, and Regen I. The Forest Regrowth group refers to LCC types which were associated with net gains in forest biomass. This includes the Regen II and Succession types.

Simulated biomass data

For investigating the relationship between potential bias from scaling and estimates of biomass change due to LCC, biomass estimates were needed for each pixel. In this study, biomass refers to live above-ground plant material expressed in Mg C ha^{-1}. We developed and assigned representative average biomass values from a forest gap model parameterized for East Siberian forests and from published values. This approach accounts for biomass change due to land-cover change (i.e. disturbance or succession from one classification category to another). Composition and biomass of forests ranging from young to mature were estimated based on simulation outputs of the FAREAST model. The FAREAST model has been tested and validated at 37 regional sites mostly in Siberia and is intended to simulate a wide range of forests across the whole of Eastern Eurasia (Yan and Shugart 2005). To apply the FAREAST model, geographic coordinates at the center of the study area were used to base 200 simulations that predicted forest composition and biomass on yearly growth increments from 0–400 years.

The simulated biomass outputs were assigned to each of the Landsat-derived forest classes (i.e., Conifer, Mixed, Deciduous and Young) in the land-cover data for 1990 and 2000 as average values. The simulated biomass values for the forest classes (Table 2) were found to be comparable to representative field measurements made by other studies (Alexeyev and Birdsey 1998). The average biomass densities of the disturbance and other land–cover classes were estimated based either on FAREAST–modeled values or those in the published literature (Table 2). We distinguished between observed disturbances that were stand-replacing (i.e., Cut and Fire) and those that were not necessarily or immediately stand-replacing (i.e., Insect). For observed Cut and Burn classes, we assumed that live forest biomass

Table 2 Above-ground (live) biomass values assigned to individual land–cover classes

Land cover	Biomass (Mg C ha^{-1})			Source
	Range		Mean (SD)	
	Min	Max		
Conifer	66.9	134.8	115.4 (14.6)	FAREAST simulation
Mixed	72.9	98.7	92.2 (8.3)	FAREAST simulation
Deciduous	43.9	100.4	74.8 (19.7)	FAREAST simulation
Young	1.9	22.3	12.1 (14.4)	FAREAST simulation
Cut	N/A	N/A	1.9 (N/A)	FAREAST simulation
Burn	N/A	N/A	1.9 (N/A)	FAREAST simulation
Insect	N/A	N/A	62.5 (N/A)	FAREAST simulation Pauley et al. 1996
Agriculture	N/A	N/A	4.6 (N/A)	Shvidenko et al. 2000
Urban	N/A	N/A	0 (N/A)	N/A
Bare	N/A	N/A	0 (N/A)	N/A

did not remain but that initial regrowth was present, and these categories were assigned a value comparable to a very early stage of Young forest. Biomass density for forests affected by insects was assigned based on the assumptions that over the landscape this may be a mixed class of varying levels of damage (Kharuk et al. 2004), and that some regeneration (predominantly birch and aspen) has occurred. Of the remaining non-forest categories, biomass density for Agriculture was assigned based on published values in the literature (Shvidenko et al. 2000); for Urban (only high-density development was classed as urban) and Bare classes, both very small categories by area, a biomass value of zero was assigned.

Analysis

Spatial characteristics of LCC

The first objective of this analysis was to characterize the spatial heterogeneity of LCC types in the East Siberian boreal forest as they were observed at the base 60 m resolution. Using the 60 m raster data, landscape pattern metrics were calculated for each LCC type in each case study site using ArcView GIS Patch Analyst extension (McGarigal and Marks 1995). Of particular interest were several metrics potentially explaining the sizes and shapes of LCC types in the study area. Mean patch size (MPS), edge density (ED), and mean shape index (MSI) were selected for illustrating spatial patterns of LCC types. While landscape metrics themselves are known to exhibit scale dependence if degraded (Wu 2004), here they were calculated at 60 m only in order to provide base information on spatial characteristics of land-cover changes in the study area.

Scale dependence of LCC

Scale dependence was defined as the measure of agreement or disagreement of an estimate derived at a coarse resolution to the same estimate at the original reference resolution (Davis et al. 1991; Walsh et al. 2001), where lower agreement is associated with greater scale dependence. The scale dependence of the estimated LCC at increasingly coarser resolutions was calculated through the conventional error matrix method, with land–cover changes identified at the coarse resolution analogous to ‘classified’ data and corresponding changes at the base 60 m resolution analogous to ‘reference’ data (Congalton and Green 1999). Pixels of each LCC type at each simulated coarser resolution were resampled back to 60 m for the comparison across resolutions. Using the above definition, lower accuracies mean lower agreement of the identified LCC, and hence higher scale dependence. Proportions of each LCC type at the base 60 m resolution and at each progressively degraded resolution were also calculated.

Scale dependence of LCC-related biomass change

Changes in modeled above-ground biomass over time (Δbiomass) at each spatial resolution were approximated by (1) the assignment of biomass values for each pixel based on its land–cover class in 1990 and 2000, respectively; (2) calculating differences between biomass values in the two years for each pixel; and (3) pooling these biomass changes by the nine LCC types. Although lands that do not undergo LCC may change in biomass over time due to within-class growth and senesence, analysis of these dynamics was outside the scope of this study, and we held the Δbiomass of the CONSTANT LCC type constant. The scale dependence of Δbiomass was examined based on the root mean squared error (RMSE) between Δbiomass quantities calculated at the 60 m and those at coarser resolutions. Pixels at coarser resolutions were resampled back to 60 m for the comparison across resolutions. Lower accuracies or higher RMSE indicate lower agreement of the calculated Δbiomass, and hence higher scale dependence.

Influence of LCC spatial characteristics on Δbiomass estimates

The landscape pattern metrics were calculated for use in evaluating the influence of the spatial characteristics of different LCC types on the bias of Δbiomass estimates. The relationships between the three metrics (i.e., MPS, ED, and MSI) calculated at 60 m and the RMSE of Δbiomass calculated at 960 m were analyzed using generalized linear regression models (GLM). The GLM dependent variable was the pixel-wise RMSE of the estimated Δbiomass averaged by LCC types for each of the three sites at 960 m. The GLM predictors included one of the three patch metrics at 60 m for each model and also a site indicator to test for differences among sites. There were 24 observations in each of the regression models, corresponding to the seven, nine, and eight existing LCC types for Tomsk, Krasnoyarsk, and Irkutsk sites, respectively.

Results

LCC and Δbiomass at 60 m

Between 1990 and 2000, approximately 20, 32, and 13% of the total area in the Tomsk, Krasnoyarsk, and Irkutsk sites, respectively, experienced changes in land–cover type (Table 3). This ranged from complete changes in state (e.g., Logged) to processes with less pronounced change in type and biomass (e.g., Regen I or Succession). In the Forest Disturbance group, a greater amount of Logged occurred in the Tomsk and Krasnoyarsk sites and less in the Irkutsk site. The largest proportion of very recent severe burns (i.e., Burned) was detected in the Irkutsk site (2.5% of the area). Only the Krasnoyarsk site experienced the Infested class during the study period (6.2% of the area). All three sites had a small amount of Developed. Interim disturbances (i.e., Regen I) occurred in all three sites. In the Forest Regrowth group, Regen II was present on 2–6% of the total land area. In all three case study sites, Succession occurred, with a larger amount occurring in Krasnoyarsk.

The average estimated Δbiomass between 1990 and 2000, based on accounting for changes in land-cover class, was 3.9 Mg C ha^{-1} pooled across the three study sites at the 60 m resolution. Among the Forest Disturbance categories, the Logged and Burned types were associated with the highest biomass losses per unit area (Table 3). Similarly, Regen I resulted in a high loss of biomass across all three sites, with relatively low biomass recovery in 2000. Infested, defined as a mixed category of varying levels of live and dead biomass plus regrowth, had a somewhat lower loss of biomass per unit area than other Forest Disturbance types. Compared to the biomass loss in the Forest Disturbance group, the biomass gained per unit area over ten years for LCC types within the Forest Regrowth group was smaller on average. However, since the amount of area in the Forest Regrowth group was two

Table 3 Changes in land cover (%) and above-ground live biomass (Mg C ha^{-1}) due to LCC at the 60 m resolution

Land-cover change	Tomsk			Krasnoyarsk			Irkutsk		
	% by area	ΔBiomass	Area-weighted ΔBiomass	% by area	ΔBiomass	Area-weighted ΔBiomass	% by area	ΔBiomass	Area-weighted ΔBiomass
Forest disturbance									
Logged	1.48	−82.14	−1.22	1.15	−64.44	−0.74	0.50	−95.83	−0.48
Burned	0.00	0.00	0.00	0.66	−56.36	−0.37	2.49	−96.13	−2.39
Infested	0.00	0.00	0.00	6.20	−30.20	−1.87	0.00	0.00	0.00
Developed	0.58	−44.19	−0.25	1.96	−44.57	−0.88	0.48	−85.93	−0.41
Regen I	2.83	−69.92	−1.98	1.40	−80.11	−1.12	0.51	−60.03	−0.31
Subtotal			*−3.45*			*−4.98*			*−3.59*
Forest regrowth									
Regen II	6.09	28.93	1.76	3.74	33.63	1.25	2.15	58.41	1.26
Succession	9.16	51.28	4.70	17.17	58.83	10.10	6.85	27.04	1.85
Subtotal			*6.46*			*11.35*			*3.11*
Unknown	4.52	−7.42	*−0.34*	6.97	4.96	*0.34*	12.76	−14.62	*−1.87*
Constant	75.35	0.00	*0.00*	60.75	0.00	*0.00*	74.26	0.00	*0.00*
*Total**			*+3.01*			*+6.37*			*−0.48*

The *subtotal* and *total* is the sum of Δbiomass weighted by proportions of area occupied by individual land-cover change types

* Excludes the Unknown and Constant types

to three times larger than the area of the Forest Disturbance group, the total biomass increment in a site due to regeneration and succession exceeded (in Tomsk and Krasnoyarsk) or was comparable (in Irkutsk) to the biomass loss due to disturbances and development (Table 3).

At the individual site level, the average simulated Δbiomass between 1990 and 2000 (based on observed land-cover changes and excluding the Unknown or Constant types) at the base 60 m resolution was estimated to be 3.01, 6.37 and −0.48 Mg C ha^{-1} for the Tomsk, Krasnoyarsk and Irkutsk sites, respectively. The slight decline in the Irkutsk site was due mainly to its large severe fires, identified as fresh burn scars in the 2000 Landsat data. The increase of biomass in the Tomsk and Krasnoyarsk sites resulted from biomass gained through forest regrowth and succession, which exceeded biomass lost through forest disturbance. Krasnoyarsk and Tomsk are sites of particularly extensive earlier logging and fire as well as abandonment of agricultural lands.

LCC spatial characteristics

The MPS, ED, and MSI metrics varied by different LCC types across the three case study sites at the 60 m resolution (Fig. 2). Because no smoothing was done on the 60 m raster LCC data, patch statistics were dominated by small patches. Across the three sites, Logged had relatively consistent MPS (4.2–5.5 ha) and shape (1.21–1.31) characteristics. Spatial characteristics of Burned varied across sites, including: (1) no severe burns could be conclusively identified in the Tomsk site during the time period of 1990–2000; (2) new burn scars were small on average (4.6 ha) in the Krasnoyarsk site, but larger (22.8 ha) in the Irkutsk site; and (3) the shape of the generally larger Burned patches was slightly more complex in the topographically more complex Irkutsk site (1.34) than in Krasnoyarsk (1.23). The MPS of Infested was relatively large in the Krasnoyarsk occurrence (11.3 ha), with intermediate MSI (1.28). For Regen I or II patches, MPS and MSI were similar in the Tomsk and Krasnoyarsk site, but different in the Irkutsk site which has more complex terrain. Constant had the greatest MPS (70.2–130.6 ha), reflecting primarily undisturbed forest lands or successional forests after large fires or earlier landscape-scale clearing.

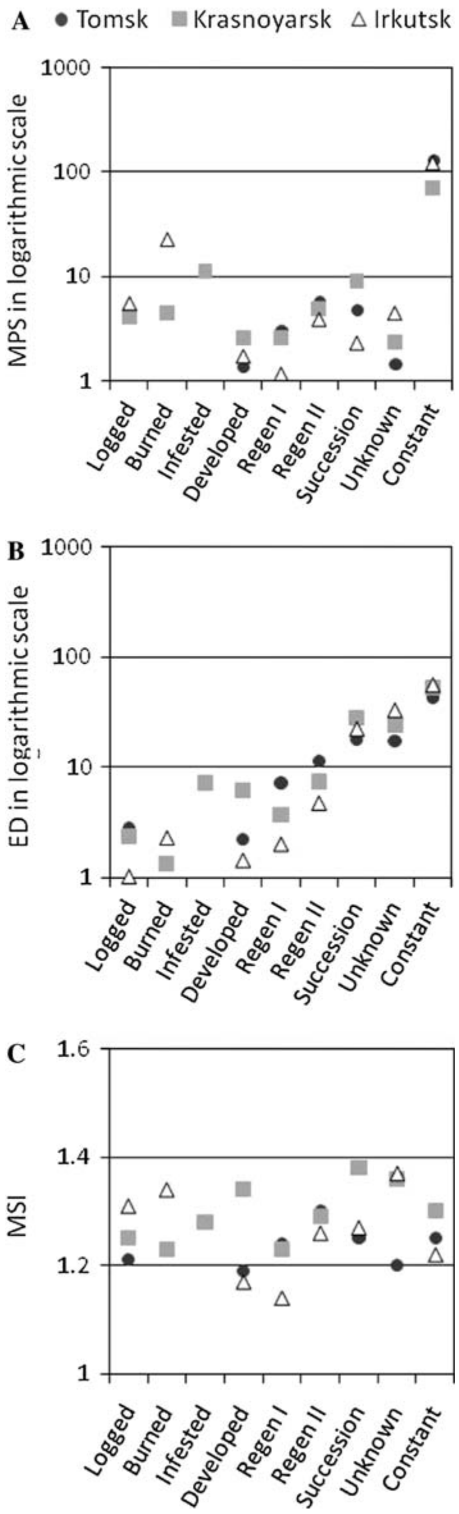


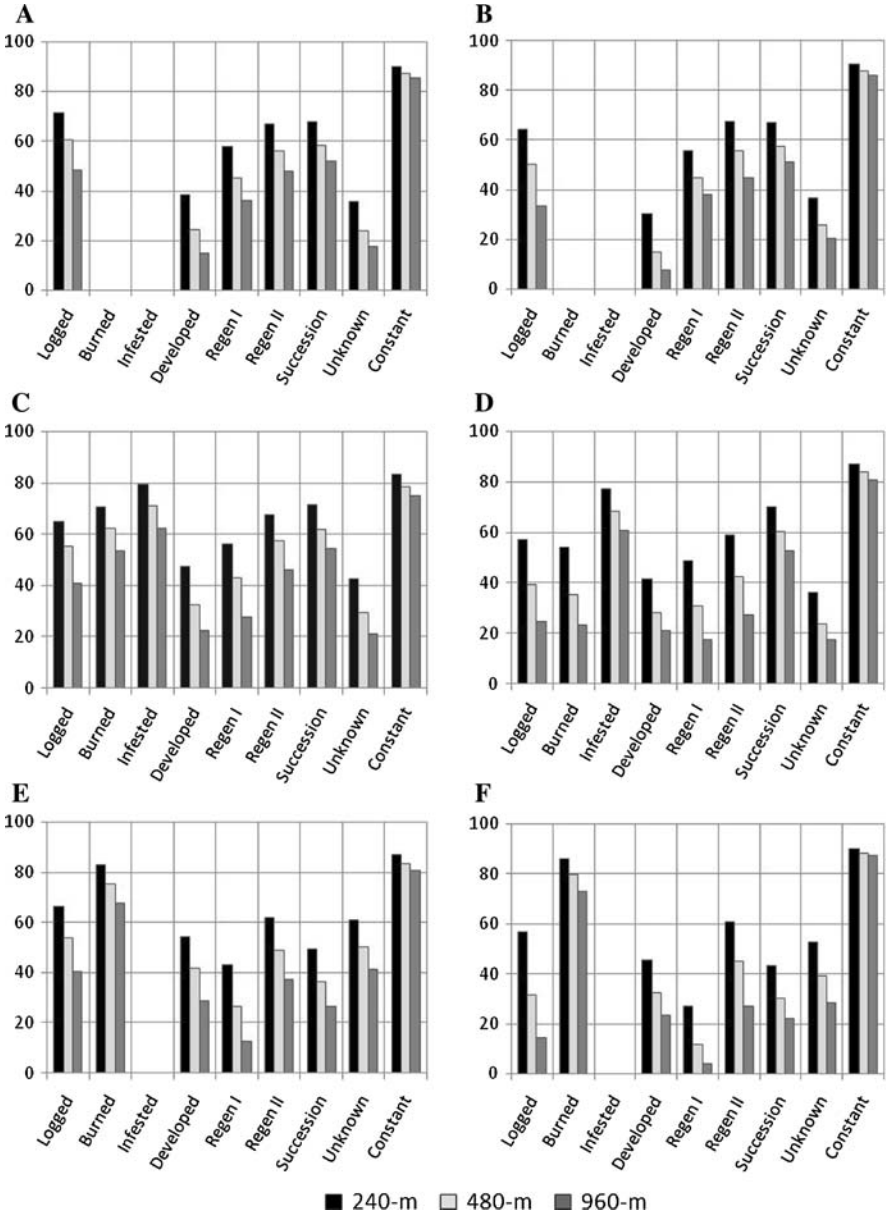
Fig. 2 **a** Mean patch size (ha), **b** edge density (m/ha), and **c** mean shape index for the three case study sites

Scaling effects on LCC estimates

For all three sites, the relatively large Constant LCC type retained a high level of agreement relative to the 60 m reference (Fig. 3a–f) and, therefore, its scale dependence was low. The Logged and Developed types had consistently low agreement at the degraded resolutions; therefore, their scale dependence was high. Producer's accuracy of the Burned type declined faster in the Krasnoyarsk site (Fig. 2d) and slower in the Irkutsk site (Fig. 2f), indicating a reduced scale dependence in the Irkutsk site which had larger Burned patches. The regeneration and succession types were also scale dependent. In the Tomsk and Krasnoyarsk sites Regen I appeared to be more scale dependent than Regen II or Succession, but all three types showed a somewhat higher sensitivity to scale in the more topographically complex Irkutsk site.

Overall agreements (i.e., indicators of scale dependence) of the detected LCCs at the coarsest 960 m resolution vs. the 60 m reference were 74.9, 65.4 and

Fig. 3 User's and Producer's accuracy of the degraded land-cover change at the 240 m (*black*), 480 m (*light grey*) and 960 m (*dark grey*) resolution for the Tomsk (**a**, **b**), Krasnoyarsk (**c**, **d**) and Irkutsk (**e**, **f**) sites. The reference is the 60 m land-cover change dataset



72.8% for the Tomsk, Krasnoyarsk and Irkutsk sites, respectively. Given that the overall accuracies of the land-cover classifications were 89–96% at the 60 m resolution, the estimated accuracies of LCC types ranged between 79 and 92% at this resolution (Table 1). Therefore, on the basis of this scale dependency analysis, accuracy of the identified land-cover changes at the 960 m resolution may vary between 52% (i.e., 0.79 × 0.654) and 69% (i.e., 0.92 × 0.749). This indicates that, based on the simulated land-cover data, scale dependence may cause a drop of approximately 20–30% in accuracy of the detectable land-cover changes using LCC data between at a resolution of 960 m vs. the 60 m reference. In terms of area, across the three sites, the Logged type was highly scale dependent and, therefore, its areas were not retained well at the degraded resolutions (Fig. 4a–c). Burned was also highly scale dependent in the Krasnoyarsk site and its area was considerably underestimated at coarser resolutions (Fig. 4b). However, Burned was less dependent on scale in the Irkutsk site, although it was overestimated at coarse resolutions (Fig. 4c). Infested in the Krasnoyarsk site had an intermediate level of scale dependence and was slightly under-represented at the degraded resolutions (Fig. 4b). Most of the remaining dynamic LCC types were underestimated, in contrast to the Constant type, which was always overestimated (Table 4).

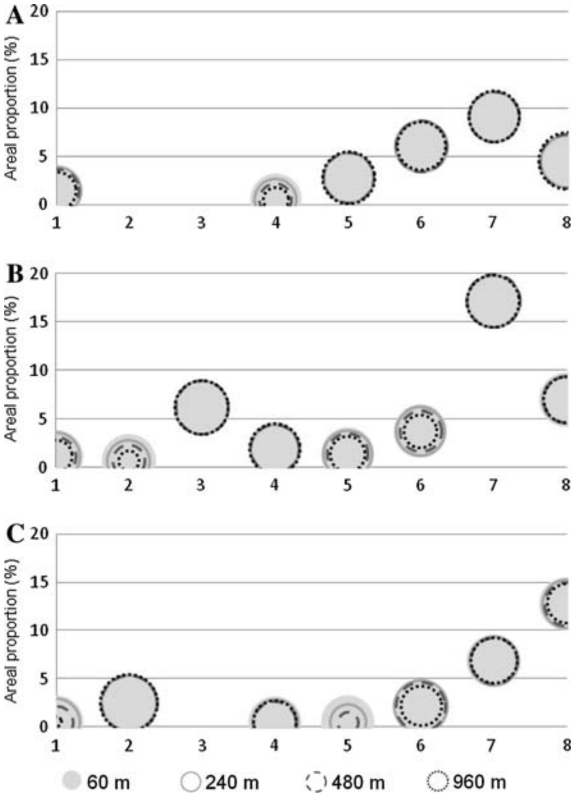


Fig. 4 Proportion of individual land-cover changes identified at the degraded spatial resolutions in the Tomsk (**a**), Krasnoyarsk (**b**) and Irkutsk (**c**) sites. The center of the *solid grey circle* corresponds to proportion of each land-cover change by area at 60 m resolution. The size (i.e., diameter) of *hollow circles* represents the reduced or increasing proportion identified at the degraded resolutions (note: magnitude of changes in proportion was exaggerated by 1.5 for the purpose of illustration). Land-cover change codes are: 1 Logged, 2 Burned, 3 Infested, 4 Developed, 5 Regen I, 6 Regen II, 7 Succession, and 8 Unknown

Scaling effects on Δbiomass estimates

With respect to simulated Δbiomass between 1990 and 2000, the estimates at the 960 m resolution were 3.30, 6.97 and -0.83 Mg C ha^{-1} for the Tomsk, Krasnoyarsk and Irkutsk sites, respectively (Fig. 5a). These were equivalent to relative differences of 9.6, 9.4 and 69.4%, compared to the Δbiomass quantities calculated at the 60 m resolution. The large change in rate for the Irkutsk site was due mainly to the small number for Δbiomass calculated at both base and degraded resolutions, i.e., -0.48 Mg C ha^{-1} at 60 m vs. -0.83 Mg C ha^{-1} at 960 m. For all three sites, the magnitude (absolute value) of the estimated Δbiomass increased with degradation of spatial resolutions (Fig. 5a). The same trend was found for the pixel-level RMSE for the estimated Δbiomass (Fig. 5b). At the coarsest (960 m) resolution, RMSE was 21.38, 30.22 and 32.12 Mg C ha^{-1} in the Tomsk, Krasnoyarsk and Irkutsk sites, respectively. This, on average, is equivalent to up to 28% of the pixel-level maximum potential biomass change (Table 2) in the study area during 1990–2000.

Relationship between scaled Δbiomass and LCC spatial characteristics

The relationships between RMSE of the estimated Δbiomass at 960 m and the three LCC pattern metrics at 60 m, based on GLM models, showed that MPS and ED were significant ($P \leq 0.001$) predictors for RMSE of Δbiomass (significant negative relationships) and that MSI was not a significant predictor

Table 4 Proportions of land-cover change types at 60 and 960 m resolutions

Land-cover change	Tomsk			Krasnoyarsk			Irkutsk		
	60 m	960 m	Difference (%)	60 m	960 m	Difference (%)	60 m	960 m	Difference (%)
LOGGED	1.48	1.02	**−30.92**	1.15	0.65	**−43.27**	0.50	0.18	**−64.27**
BURNED	0.00	0.00	**N/A**	0.66	0.28	**−57.14**	2.49	2.71	**8.61**
INFESTED	0.00	0.00	**N/A**	6.20	6.06	**−2.36**	0.00	0.00	**N/A**
DEVELOPED	0.58	0.29	**−51.15**	1.96	1.81	**−7.49**	0.48	0.36	**−25.38**
REGEN I	2.38	2.89	**2.03**	1.40	0.88	**−37.56**	0.51	0.16	**−69.95**
REGEN II	6.09	5.68	**−6.73**	3.74	2.19	**−41.51**	2.15	1.53	**−29.00**
SUCCESSION	9.16	9.05	**−1.19**	17.17	16.65	**−3.02**	6.85	5.63	**−17.81**
UNKNOWN	4.52	5.26	**16.49**	6.97	5.71	**−18.19**	12.76	13.50	**5.80**
CONSTANT	75.35	75.81	**0.62**	60.75	65.78	**8.28**	74.26	75.95	**2.27**

Their differences in proportion with respect to their 60 m proportion are shown in bold numbers, where negative values indicate under-estimation of area at the 960 m resolution and positive values over-estimation

(Table 5). Higher levels of agreement were associated with the large-sized LCC (i.e., high MPS values), indicating that large-sized changes (including the CONSTANT type) were less prone to errors of identification at degraded resolutions. ED was also significantly negatively related to RMSE, meaning that the error of estimated Δbiomass was high for LCC types with low edge densities. Low agreement of the estimated Δbiomass of LOGGED occurred at the coarse spatial resolution not because of its simple edges, though they were well correlated, but because of the loss of logging due to its small patch sizes. The site predictor was not significant, based on GLM models. Thus relationships between RMSE and patch indices were consistent across the three sites, indicating the regional generalizability of scaling influence on errors of the estimated Δbiomass rather than specific spatial characteristics of a site.

Discussion

Scaling and amplified estimates at coarser resolutions

One impetus for this study was that research investigating the influences of scaling on estimates of LCC and carbon change has appeared to yield divergent conclusions, including apparent overestimation (Caylor and Shugart 2004; Ahl et al. 2005) and underestimation (Turner et al. 2000; Zhang et al. 2003) of LCC or carbon-related variables. Our results illustrate why this divergence of LCC estimates may occur, and that it is influenced by the landscape characteristics associated with the LCC types being observed. For example, all LCC types in the Forest Disturbance group, except for a few cases of BURNED and likely large fire-related REGEN I patches, were quite dependent on scale and were underestimated at the 960 m resolution (Table 4). Fire patches in Krasnoyarsk were relatively small in raster patch size (4.6 ha on average); therefore >50% of these clusters of fire pixels disappeared at the 960 m resolution. On the contrary, fire patches in Irkutsk were large in size (22.8 ha on average), which resulted in an overestimation of the burned area by about 9% at the 960 m resolution.

No divergent trends in Δbiomass were detected in our study; instead, Δbiomass was shown to be consistently overestimated at degraded resolutions across the three case study sites regardless of whether its direction was an increase or decline in actual biomass (Fig. 5a). The underestimation of LCC types in the Forest Disturbance group (except the BURNED type) contributed to overestimation of the positive Δbiomass at coarse resolutions. The small-sized BURNED type enhanced the overestimation of positive Δbiomass at coarse resolutions in Krasnoyarsk, while its larger size in Irkutsk resulted in the overestimation of negative Δbiomass at coarse resolutions in that site.

All LCC categories in the Forest Regrowth group were underestimated at the 960 m resolution, but at a smaller rate compared to the Forest Disturbance

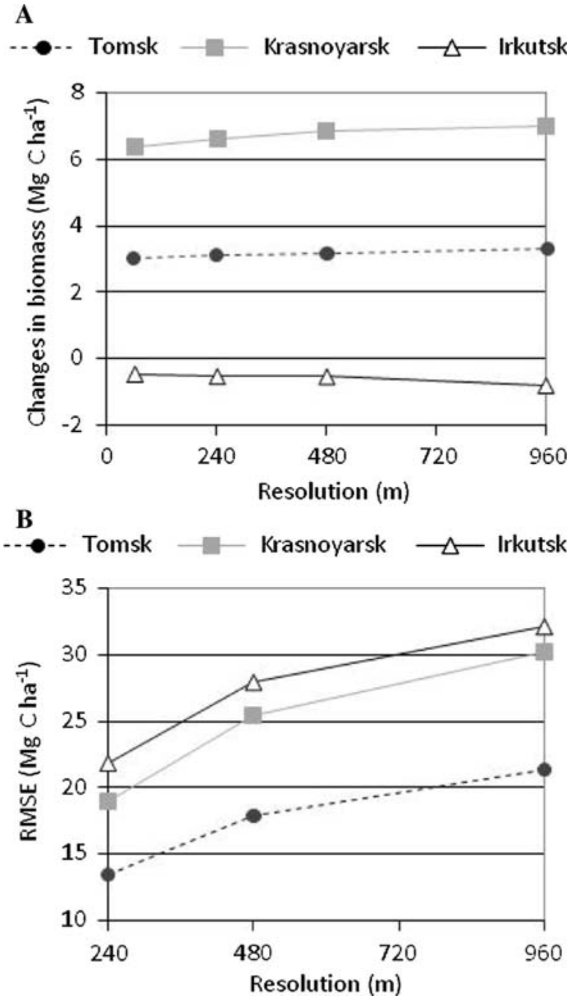


Fig. 5 Estimated Δbiomass (above-ground live; Mg C ha^{-1}) at 60 m and degraded resolutions (**a**) and its RMSE with the 60 m estimates at degraded resolutions (**b**)

group (Table 4). In other words, the Forest Regrowth types and the large-sized Forest Disturbance types (such as INFESTED and large BURNED patches) retained presence better than the small-sized disturbances (such as the DEVELOPED, recently LOGGED and small BURNED patches). Therefore, when aggregating from 60 to 960 m, in most cases there is an overestimation of biomass increase at the degraded spatial resolutions except for areas with extensive and spatially continuous disturbance (Fig. 5a).

These results imply that, at the degraded spatial resolution, information on disturbances may be under- or over-estimated depending on their average patch sizes and, consequently, the estimated value of changes in biomass at the coarse resolutions may be amplified regardless of the change directions. As other researchers have suggested (Harmon 2001), more accurate quantification of LCC and carbon-related assessments in boreal forests of Northern Eurasia requires assessments taking into account LCC scale and spatial heterogeneity.

Table 5 Regression model results for the relationship between RMSE of the estimated Δbiomass at 960 m and patch metrics of individual LCC types at 60 m

GLM	Adjusted R^2	Variable	Significance
1	0.411	Complete model	0.003
		MPS	0.001
		Site	0.152
2	0.528	Complete model	0.000
		ED	0.000
		Site	0.141
3	−0.030	Complete model	0.520
		MSI	0.469
		Site	0.429

The pixel–wise RMSE was pooled by LCC types at each case study site. In all three models, RMSE is the dependent variable. Independent variables include patch metric and site indicator. The adjusted *R* square is the indicator of model fit

Methods and extensibility

In order to meet our study objectives several established methods were used in a novel combination to investigate our research questions. We used an existing Landsat-derived LCC dataset, modeled biomass values, and a method using degraded image resolutions. Validated LCC data at high, or even moderate, spatial resolutions are not widely available for Siberian Russia, and so the 1990 and 2000 land-cover datasets used in this study provided an unusual opportunity to analyze the boreal forest disturbances and regrowth representative of the East Siberia over a range of years corresponding to the recent land-cover change regime.

While the land–cover and LCC data had reasonable accuracy statistics, classification errors are one of the uncertainties associated with estimates of LCC and LCC-related Δbiomass in the present study (Table 1). There are several potential scaling methods; for our scaling method, we used a method involving degrading of the existing 60 m LCC data in order to minimize complications that otherwise would undoubtedly be present in a methodology that relied on multiple new classifications of progressively degraded image data. The LCC data available to us was based on Landsat TM/ETM+ 30 m imagery that had been resampled to 60 m prior to classification to be spatially congruent with a time-series MSS 60 m dataset. Therefore, while based on the Landsat TM/ETM+ spectral resolution, because there is only a small scale difference between the two, present results are likely very similar to, but not exactly interpretable at the Landsat TM/ETM+ 30 m spatial resolution.

Although the degraded LCC data are not intended to simulate data derived from existing coarse resolution sensors, the results of this study may shed light on uncertainties related to the large–area monitoring of biomass changes in coarse spatial resolution sensors such as MODIS or AVHRR. For this purpose, there are two limitations to note. First, a simulated point spread function (PSF) was used for estimation of coarse image pixels, and is not identical to the PSF of actual sensors. Second, spectral information of the Landsat TM/ETM+ differs somewhat from the above coarser resolution sensors. Where our data are of higher spectral resolution than coarser spatial resolution sensors, it might be hypothesized that our results (both moderate spectral and spatial resolution) present a best case scenario with respect to LCC estimates at these scales. Future work could include comparison of the results of this study with studies accounting for both spatial scale and spectral resolution. It could be interesting to assess where the trade-off between spectral resolution and spatial scale may converge over similar landscapes.

Conclusions

In this study we investigated land-cover and biomass changes between 1990 and 2000 in three case study sites representative of East Siberia, and analyzed the influence of remote sensing data spatial resolution on the estimated LCC and LCC-related above-ground Δbiomass of this region. We found that, based on reference land-cover data at 60 m, modeled above-ground biomass increased in two of the case study sites and declined in the third one. The increase of biomass in the first two sites was due to the greater gain of biomass from forest regrowth compared with the loss of biomass to forest disturbances. The decline of biomass quantity in the third site was can be attributed mainly to its large-sized forest fires as well as the relatively low regrowth in this site.

The importance of scale in quantifying land-cover and biomass changes was confirmed in this study. Accuracy of LCC was estimated to decrease by 20–30% due to scaling alone from 60 to 960 m. Error of the pixel-wise Δbiomass at 960 m was about 30% of the maximum magnitude of possible changes derived at 60 m. We also found that the loss of information on small-sized disturbances or development contributed to the overestimation of positive Δbiomass by 9–10% at 960 m, and that a single large-extent disturbance such as forest fires may produce the overestimation of this disturbance by 9% in area and cause the overestimation of negative Δbiomass at the degraded resolution. Our conclusions support the earlier findings about scaling effects of remote sensing data on LCC inference, i.e., the small-sized features tend to be underestimated at resolutions coarser than the feature. Moreover, we found that the biased LCC data, when propagated to the estimation of Δbiomass, tends to cause an overestimation of Δbiomass at coarse resolutions.

Given that the three case study sites represented a range of southern East Siberia forest situations and that the site predictor was not significant, the results of this study should be extensible to similar forested landscapes in the region. Recent progress has been made in using coarse resolution (1 km) data in surveys of land cover and LCC, including in boreal Eurasia (Bartalev et al. 2003; Achard et al. 2006). Fine or moderate resolution data collected within the coarse image footprint at approximately the same times would yield quantification of changes that may be used to infer uncertainties associated with the coarse resolution data. By this means, LCC and associated changes in carbon may be estimated in an efficient way using coarse resolution data with the known details of any bias due to sensor spatial resolution provided through scaling analyses similar to those conducted in our paper.

Acknowledgments This study was supported by the NASA Land–Cover/Land–Use Change Program through contract NAG5–11084. We extend appreciation to Dr. G. Gutman, NASA LCLUC Program; Dr. E. Vaganov and Dr. V. Kharuk of the V. N. Sukachev Institute of Forest, Siberian Branch, Russian Academy of Sciences; and S. Brines and D. Robinson at the University of Michigan ESALab.

References

Achard F, Mollicone D, Stibig HJ et al (2006) Areas of rapid forest-cover change in boreal Eurasia. For Ecol Manage 237:322–334

Ahl DE, Gower ST, Mackay DS et al (2005) The effects of aggregated land cover data on estimating NPP in northern Wisconsin. Remote Sens Environ 97:1–14

Alexeyev VA, Birdsey RA (1998) Carbon storage in forests and peatlands of Russia. USDA Forest Service, Washington, p 137

Alpin P (2006) On scales and dynamics in observing the environment. Int J Remote Sens 27:2123–2140

Atkinson PM, Curran PJ (1997) Choosing an appropriate spatial resolution for remote sensing investigations. Photogramm Eng Remote Sens 63:1345–1351

Bartalev SA, Belward AS, Erchov DV et al (2003) A new SPOT4-VEGETATION derived land cover map of Northern Eurasia. Int J Remote Sens 24:1977–1982

Bergen KM, Zhao TT, Kharuk V et al (2008) Changing regimes: forested land-cover dynamics in Central Siberia 1974–2001. Photogramm Eng Remote Sens 74:787–798

Caylor KK, Shugart HH (2004) Simulated productivity of heterogeneous patches in Southern African savanna landscapes using a canopy productivity model. Landscape Ecol 19:401–415

Conard SG, Ivanova GA (1997) Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia. Clim Change 1:197–211

Congalton RG, Green K (1999) Assessing the accuracy of remotely sensed data: principles and practices. Lewis Publications, Boca Raton

Davis FW, Quattrochi DA, Ridd MK et al (1991) Environmental-analysis using integrated GIS and remotely sensed data–some research needs and priorities. Photogramm Eng Remote Sens 57:689–697

Harmon ME (2001) Carbon sequestration in forests–addressing the scale question. J For 99:24–29

Hassan R, Scholes RJ, Ash N (eds) (2005) Millennium ecosystem assessment: ecosystems and human well-being. Island Press, Washington

Huang CQ, Townshend JRG, Liang SL et al (2002) Impact of sensor's point spread function on land cover characterization: assessment and deconvolution. Remote Sens Environ 80:203–212

Hytteborn H, Maslov AA, Nazimova DI (2005) Boreal forests of Eurasia. In: Anderssen F et al (eds) Ecosystems of the world: coniferous forests. Elsevier, Amsterdam, pp 23–99

Justice CO, Markham BL, Townshend JRG et al (1989) Spatial degradation of satellite data. Int J Remote Sens 10:1539–1561

Kharuk VI, Ranson KJ, Kozuhovskaya AG et al (2004) NOAA/AVHRR satellite detection of Siberian silkmoth outbreaks in eastern Siberia. Int J Remote Sens 25:5543–5555

Kharuk VI, Ranson KJ, Fedotova EV (2007) Spatial pattern of Siberian silkmoth outbreak and taiga mortality. Scand J For Res 22:531–536

Krankina ON, Harmon ME, Cohen WB et al (2004) Carbon stores, sinks, and sources in forests of northwestern Russia: can we reconcile forest inventories with remote sensing results? Clim Change 67:257–272

Krankina ON, Houghton RA, Harmon ME et al (2005a) Effects of climate, disturbance, and species on forest biomass across Russia. Can J For Res 35:2281–2293

Krankina ON, Sun G, Shugart HH et al (2005b) Northern Eurasia: remote sensing of boreal forest in selected regions. Land change science: observing, monitoring and understanding trajectories of change on the earth's surface. Kluwer, Dordrecht, Netherlands, pp 123–138

McGarigal K, Marks BJ (1995) FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. US Department of Agriculture, US Forest Service, Portland, p 122

Nelson R, Holben B (1986) Identifying deforestation in Brazil using multiresolution satellite data. Int J Remote Sens 7: 429–448

Olson DM, Dinerstein E, Wikramanayake ED et al (2001) Terrestrial ecoregions of the world: a new map of life on earth. Bioscience 51:933–938

Pauley EF, Nodvin SC, Nicholas NS et al (1996) Vegetation, biomass, and nitrogen pools in a spruce-fir forest of the Great Smoky Mountains National Park. Bull Torrey Bot Club 123:318–329

Peterson LK, Bergen KM, Brown DG et al (2009) Forested land-cover patterns and trends over changing forest management eras in the Siberian Baikal region. For Ecol Manage 257: 911–922

Ranson KJ, Kovacs K, Sun G et al (2003) Disturbance recognition in the boreal forest using radar and Landsat-7. Can J Remote Sens 29:271–285

Shvidenko AZ, Nilsson S, Stolbovoi VS et al (2000) Aggregated estimation of the basic parameters of biological production and the carbon budget of Russian terrestrial ecosystems: Stocks of plant organic mass. Russ J Ecol 31:371–378

Steyaert LT, Hall FG, Loveland TR (1997) Land cover mapping, fire regeneration, and scaling studies in the Canadian boreal forest with 1 km AVHRR and Landsat TM data. J Geophys Res 102:29581–29598

Strahler AH, Woodcock CE, Smith JA (1986) On the nature of models in remote-sensing. Remote Sens Environ 20:121–139

Turner DP, Cohen WB, Kennedy RE (2000) Alternative spatial resolutions and estimation of carbon flux over a managed forest landscape in Western Oregon. Landscape Ecol 15: 441–452

USGS (1996) GTOPO30. Sioux Falls, USA

Walsh SJ, Crawford TW, Welsh WF et al (2001) A multiscale analysis of LULC and NDVI variation in Nang Rong district, northeast Thailand. Agric Ecosyst Environ 85:47–64

Woodcock CE, Strahler AH (1987) The factor of scale in remote-sensing. Remote Sens Environ 21:311–332

Wu JG (2004) Effects of changing scale on landscape pattern analysis: scaling relations. Landscape Ecol 19:125–138

Yan X, Shugart HH (2005) FAREAST: a forest gap model to simulate dynamics and patterns of eastern Eurasian forests. J Biogeogr 32:1641–1658

Yaroshenko AY, Potapov PV, Turubanova SA (2001) The last intact forest landscapes of northern European Russia. Greenpeace Russia and Global Forest Watch, Moscow, p 75

Zhang YH, Wooster MJ, Tutubalina O et al (2003) Monthly burned area and forest fire carbon emission estimates for the Russian Federation from SPOT VGT. Remote Sens Environ 87:1–15