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Estimating aboveground carbon in a catchment of the Siberian forest tundra: Combining satellite imagery and field inventory

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ABSTRACT

This study was part of an interdisciplinary research project on soil carbon and phytomass dynamics of boreal and arctic permafrost landscapes. The 45 ha study area was a catchment located in the forest tundra in northern Siberia, approximately 100 km north of the Arctic Circle.
The objective of this study was to estimate aboveground carbon (AGC) and assess and model its spatial variability. We combined multi-spectral high resolution remote sensing imagery and sample based field inventory data by means of the *k*-nearest neighbor (*k*-NN) technique and linear regression.
Field data was collected by stratified systematic sampling in August 2006 with a total sample size of $n=31$ circular nested sample plots of 154 m^2 for trees and shrubs and 1 m^2 for ground vegetation. Destructive biomass samples were taken on a sub-sample for fresh weight and moisture content. Species-specific allometric biomass models were constructed to predict dry biomass from diameter at breast height *(dbh)* for trees and from elliptic projection areas for shrubs.
Quickbird data (standard imagery product), acquired shortly before the field campaign and archived ASTER data (Level-1B product) of 2001 were geo-referenced, converted to calibrated radiances at sensor and used as carrier data. Spectral information of the pixels which were located in the inventory plots were extracted and analyzed as reference set. Stepwise multiple linear regression was applied to identify suitable predictors from the set of variables of the original satellite bands, vegetation indices and texture metrics. To produce thematic carbon maps, carbon values were predicted for all pixels of the investigated satellite scenes. For this prediction, we compared the *k*NN distance-weighted classifier and multiple linear regression with respect to their predictions.
The estimated mean value of aboveground carbon from stratified sampling in the field is 15.3 t/ha (standard error SE=1.50 t/ha, SE%=9.8%). Zonal prediction from the *k*-NN method for the Quickbird image as carrier is 14.7 t/ha with a root mean square error RMSE=6.42 t/ha, $RMSE_r$=44%) resulting from leave-one-out cross-validation. The *k*-NN-approach allows mapping and analysis of the spatial variability of AGC. The results show high spatial variability with AGC predictions ranging from 4.3 t/ha to 28.8 t/ha, reflecting the highly heterogeneous conditions in those permafrost-influenced landscapes. The means and totals of linear regression and *k*-NN predictions revealed only small differences but some regional distinctions were recognized in the maps.

1. Introduction

Forest ecosystems are an important part of the global carbon cycle because they store a large part of the total terrestrial organic carbon and exchange CO_2 with the atmosphere. In permafrost regions carbon storage and net-exchange of CO_2 may change considerably due to the predicted temperature increase of 6 to 7 °C within the next 100 years (IPCC, 2007). Permafrost thaw and the related deepening of the active layer are expected to increase CO_2 emission from organic matter mineralization in the soil (Hobbie et al., 2000) but there is potential increase of carbon storage in plant biomass (White et al., 2000).

There are considerable uncertainties and knowledge gaps regarding the influence of current and future permafrost dynamics on the processes of carbon emission and carbon sequestration in northern ecosystems. Monitoring the vegetation dynamics of the circumpolar boreal forest (northern taiga) and arctic tundra region is important for understanding the consequences of climate-driven changes in these areas (Ranson et al., 2004). The transitional region of the forest tundra is expected to be sensitive to even small changes in environmental variables and thus it can offer early insight into potential changes in vegetation and aboveground carbon stocks driven by climate change.

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1.1. Estimation of aboveground carbon (AGC)

Information about the amount and distribution of aboveground phytomass is a prerequisite for the evaluation of the role of carbon exchange rates and for realistic predictions of future climate changes. Vaganov et al. (2006) report that in 2006 more than 20 international research projects dealt with this issue in Siberia. There are two primary methods for the assessing of phytomass: (1). field measurements, and (2) indirect assessments using remote sensing techniques.

Camill and Clark (1998) showed that local factors such as slope, aspect and successional patterns have a stronger influence on boreal permafrost peatland dynamics than the regional mean annual temperature. Therefore, studies describing processes on a local scale are of great importance for calibration and validation of ecosystem models.

1. Field measurements: Aboveground carbon stock (AGC) cannot be measured directly but must be derived from aboveground biomass (AGB). For ecosystem level biomass assessments there are numerous techniques two of which have been applied in the context of boreal and arctic regions:
   (a.) Biomass expansion factors (BEF) are derived from the relationship between easy to measure variables such as stand volume and AGB. They are widely used (Alexeyev et al., 1995; Alexeyev & Birdsey, 1998; Houghton et al., 2007; Isaev et al., 1995; Monserud et al., 1996; Nilsson et al., 2000). Alexeyev et al. (2000) distinguishes the geobotanical method and the forest inventory method further.
      - The geobotanical method uses a stratification based on vegetation and soil criteria. Data from a network of field plots serve for the assessment of the mean stock per stratum and the extrapolation to the strata. Selection of field plots does not necessarily follow probability sampling but is based on geobotanical criteria. For example, this method was used by Bazilevich (1993) to describe the productivity of the vegetation in Russia.
      - The forest inventory method is based on two data sources: probability sampled forest inventory plots and experimental plots where AGB of different life forms is estimated. The relationship between forest inventory data and measured carbon stocks is used to derive expansion factors. Often growing stock expressed in terms of tree volume is used as an inventory variable (Turner et al., 1995). Alexeyev et al. (1994) for example conducted a large study in Russia with 2290 sample plots.

   (b.) Allometric models for estimation of AGB are also very common (Camill et al., 2001; Fehrmann, 2006; Kajimoto et al., 2006; Montagu et al., 2005; Ohmann et al., 1976; Jia & Akiyama, 2005 ; Wirth et al., 1999). Biomass is predicted by these models on a per plot or per individual plant basis. Therefore, usually, species or site-specific models are developed by fitting parametric regression models to the relationship between AGB and easy to measure plant variables such as diameter at breast height, *dbh*.

2. Remote sensing applications: High latitude permafrost regions are difficult to access. Therefore, since the 1970s, remote sensing data have been used for monitoring these areas in addition to field measurements (Lu, 2006). It is important to note, however, that any remote sensing approach for biomass estimation also depends on field measurements.

Ahern et al. (2000) summarize the capability of optical remote sensing sensors for monitoring carbon cycles of boreal forests and identify the following features that can be assessed:

- Forest cover and biomass spatial distribution (when supported by field observations),
- Patterns of disturbance (fire, insect, land clearing),
- Pattern and rate of regrowth after disturbance,
- Seasonal variations of the net primary production.

The importance of remote sensing for AGB estimation has increased considerably during the last years due to better availability and coverage and finer geometric resolution of remote sensing data (Lu et. al., 2002; Muukkonen & Heiskanen, 2005; Nelson et al., 1988; Wulder et al., 2008; Zheng et al., 2004). The application of remote sensing has the distinct advantage that large areas can be monitored (Hese et al., 2005) and spatial variability much better characterized than when using field inventory data exclusively—always assuming that imagery with adequate spatial, spectral and radiometric characteristics is available.

There are numerous examples of approaches to estimate AGB from satellite data (Lu, 2006). Regression analysis is the most common modeling approach (Dong et al., 2003; Lu, 2005; Muukkonen & Heiskanen, 2005; Rahman et al., 2005; Zheng et al., 2004) but an increasing number of studies use the nonparametric *k*-nearest neighbor technique (*k*-NN) for regionalization (Cabaravdic, 2007; Finley et al., 2006; Tomppo et al., 2002; Tuominen & Pekkarinen, 2005). The basic idea is to estimate the unknown value of an attribute of an object based on its similarity to objects with known values of the attribute. *k*-NN methods are easy to implement in computer software in principle, although the computational demands are high and the formulation of error components is still a challenge (McRoberts et al., 2007; Stage & Crookston, 2007).

Most applications of *k*-NN for remote sensing data use medium resolution imagery such as Landsat images (Finley et al., 2006; Franco-Lopez et al., 2001; Katila & Tomppo, 2001; Mäkelä & Pekkarinen, 2001). The availability, low cost and large swath width of Landsat satellite sensors make them more appropriate for nationwide inventories. Only few studies have used fine resolution imagery such as Quickbird or aerial photographs (Muinonen et al., 2001; Tuominen & Pekkarinen, 2005). Since digital aerial photographs are widely available it is interesting to contrast medium resolution ASTER satellite images (comparable to Landsat) with high resolution Quickbird satellite images to improve prediction on a regional and local scale.

1.2. Objectives

In the framework of an interdisciplinary research project, soil carbon stocks and fluxes were analyzed in a relatively small study area in the forest tundra zone of central Siberia. There are three objectives of this particular study. The primary objective is to estimate and regionalize aboveground dry biomass and carbon stocks in a small catchment where no prior forest inventory data are available using field observations and remote sensing.

The second objective was to apply the *k*-NN-technique for estimation and regionalization of AGC as well as to quantify and model ecosystem fluxes and budgets. For the latter, AGC was to be mapped with a fine spatial resolution. The prediction accuracy of the *k*-NN technique was then compared to the accuracy of multiple regression techniques and to the accuracy of field-based stratified estimates.

The third objective was to compare the utility of data obtained from medium and high resolution satellite sensors for AGC estimation.

2. Materials and methods

2.1. Study site

The 45 ha study site is the catchment of Little Grawijka Creek in Central Siberia near the town of Igarka at 67°48′ latitude and 86°43′ longitude on the east shore of lower Yenissej River, approximately 100 km north of the Arctic Circle. It belongs to the