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Modeling forest above-ground biomass dynamics using multi-source data and incorporated models: A case study over the qilian mountains

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ABSTRACT

In this work, we present a strategy for obtaining forest above-ground biomass (AGB) dynamics at a fine spatial and temporal resolution. Our strategy rests on the assumption that combining estimates of both AGB and carbon fluxes results in a more accurate accounting for biomass than considering the terms separately, since the cumulative carbon flux should be consistent with AGB increments. Such a strategy was successfully applied to the Qilian Mountains, a cold arid region of northwest China.

Based on Landsat Thematic Mapper 5 (TM) data and ASTER GDEM V2 products (GDEM), we first improved the efficiency of existing non-parametric methods for mapping regional forest AGB for 2009 by incorporating the Random Forest (RF) model with the *k*-Nearest Neighbor (*k*-NN). Validation using forest measurements from 159 plots and the leave-one-out (LOO) method indicated that the estimates were reasonable ($R^2 = 0.70$ and RMSE = 24.52 tones ha^{-1}). We then obtained one seasonal cycle (2011) of GPP ($R^2 = 0.88$ and RMSE = 5.02 $gC\, m^{-2}\, 8d^{-1}$) using the MODIS MOD_17 GPP (MOD_17) model that was calibrated to Eddy Covariance (EC) flux tower data (2010). After that, we calibrated the ecological process model (Biome-BioGeochemical Cycles (Biome-BGC)) against above GPP estimates (for 2010) for 30 representative forest plots over an ecological gradient in order to simulate AGB changes over time. Biome-BGC outputs of GPP and net ecosystem exchange (NEE) were validated against EC data ($R^2 = 0.75$ and RMSE = 1. 27 $gC\, m^{-2}\, d^{-1}$ for GPP, and $R^2 = 0.61$ and RMSE = 1.17 $gC\, m^{-2}\, d^{-1}$ for NEE). The calibrated Biome-BGC was then applied to produce a longer time series for net primary productivity (NPP), which, after conversion into AGB increments according to site-calibrated coefficients, were compared to dendrochronological measurements ($R^2 = 0.73$ and RMSE = 46.65 $g\, m^{-2}\, year^{-1}$). By combining these increments with the AGB map of 2009, we were able to model forest AGB dynamics. In the final step, we conducted a Monte Carlo analysis of uncertainties for interannual forest AGB estimates based on errors in the above forest AGB map, NPP estimates, and the conversion of NPP to an AGB increment.

1. Introduction

Forest above-ground biomass (AGB) plays an important role in carbon and water cycles in the terrestrial biosphere. AGB impacts gross (GPP) and net primary production (NPP), the radiation balance, water interception, and even air quality (Houghton et al., 2000). Forest AGB, in turn, is affected by these processes (Vanderwel et al., 2013). The significance of the interactions between AGB and climate are better understood if spatially and temporally explicit knowledge of forest AGB, as well as its dynamics, is available. Such knowledge is of great value for understanding processes and for accomplishing scientific and practical tasks in forest management.

Forest AGB dynamics can be described as continuous or gradual (i.e., growth) and discontinuous or abrupt (i.e., disturbance) variations

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(Wulder et al., 2007) that, together, result in variations in the productivity and carbon fluxes of forests (Misson et al., 2005; Main-Knorn et al., 2013). Disturbances include fires and other natural disasters, and tree felling or planting. For this study, we focused on gradual changes in forest AGB.

At present, several techniques exist for quantifying changes and either making use of direct estimates for changes in AGB or analyzing the fluxes of CO_2 between air and land surfaces. The traditional method utilized for detecting forest AGB dynamics has been inventory-based forest sample surveys. However, obtaining reliable dynamic estimates with a satisfactory spatial and temporal resolution requires a considerable investment in labor and supplies (Riemann et al., 2010).

The Eddy Covariance (EC) technique provides estimates of CO_2, water, and energy fluxes between the biosphere and atmosphere that are essential for characterizations and dynamic analyses of forest ecosystem processes (Lee, 1998; Lee et al., 1999). In spite of this, EC techniques provide net CO_2 flux measurements over specific footprint areas, so it is impossible to upscale flux observations to large areas (Osmond et al., 2004).

The remote sensing of biophysical variables has been key for quantifying forest structure, stem volume, AGB, physiology, and carbon fluxes in forests (Goetz and Prince, 1996; Solberg et al., 2013; Liang et al., 2015), especially for situations where a finer temporal-interval and a spatial-resolution assessment of forest AGB and its dynamics are required for environmental protection (Neeff et al., 2005). Two types of remote sensing methods can be applied for estimating forest AGB dynamics. One is the repeat acquisition of remote sensing data for estimating AGB changes in carbon pools (Main-Knorn et al., 2013). The other is applying an ecological model for carbon flux simulations driven by vegetation indices (e.g. leaf area index (LAI) and the fraction of photosynthetically active radiation (*f*PAR), etc.) (Prince and Goward, 1995; Veroustraete et al., 2002). Models for carbon fluxes with detailed ecological processes contain vegetation functional mechanisms for gas exchange, photosynthesis, biomass allocation (Thornton et al., 2002), and forest responses to climate change (Braswell et al., 2005; Ueyama et al., 2009). However, exploiting the strength of these models is not easy because the models themselves require a large number of input variables and site specific calibration (White et al., 2000).

The limitations of the above mentioned methods and data sources (EC, process models, field inventories, and remote sensing data) can be partly alleviated using synergistic integration. Process models and EC measurements of carbon fluxes provide a continuous time series. Process models also constrain (gradual) AGB increments to physically realistic limits. Field inventory data are required in order to parameterize and calibrate process models, and to provide an AGB map, although output is unresolved in the temporal domain. Remote sensing data such as LAI also provide a means for constraining estimates of AGB increments through a relationship to carbon fluxes.

In this work, we propose a method for modeling a space-time series of forest AGB dynamics together with forest carbon fluxes in both the temporal and spatial domain. The proposed method is particularly relevant to our study area: an oasis in the central Asian continent whose water originates from a forest covered mountain range. Forests in the area are scattered and difficult to access. Yet, understanding the dynamics of the area is important for sustainable management. The method presented may be suitable for other areas. For the proposed method, all of the techniques and the data mentioned above were used in synergy and included: (i) forest inventory measurements (tree height, DBH, LAI, core rings, etc.); (ii) EC measurements (GPP, NEE, etc.); (iii) remotely sensed data (Landsat Thematic Mapper 5 (TM)) and refined products (MODIS LAI, *f*PAR, etc.); and (iv) refined meteorological estimates (temperature, solar radiation, precipitation, etc.). All of the steps in the method were essential for obtaining AGB estimates that were differentiated in space and time.

Key to our method was combining forest AGB estimations on one hand and accumulated carbon flux simulations on the other. For forest AGB estimations, the Random Forest (RF) method was applied to preselect the most relevant remotely sensed features. Selected features were then employed in optimizing the *k*-nearest neighbor (*k*-NN) configuration. Combining RF and k-NN improves the efficiency for estimating regional forest AGB using high-dimensional, multi-mode remote sensing information by: (i) reducing the complexity of computation for prediction, (ii) removing information redundancy (cost savings), and (iii) avoiding the issue of overfitting (Li et al., 2011). For forest carbon flux simulations, an existing remotely sensed GPP model, MODIS MOD_17, was refined and was then employed to globally calibrate the process-based model, the Biome-BioGeochemical Cycles (Biome-BGC). The process model provided a time series of maps for AGB increments. This incorporation was capable of suppressing model ill-behaviors and, strengthening model robustness, and made the model more resistant to the impacts of environmental variability and forest stand diversity that tend to create bias in simulations.

Although the proposed modeling methodology has the above advantages, models and data from multiple sources cascaded together, leading to a very complex result. Therefore, in practice, strict quality-control for each model and dataset in this systematic modeling strategy should be conducted because each introduces uncertainty in model performance. To date, most studies have assessed uncertainties in estimated forest AGB or carbon storage/density over broad scales (Monni et al., 2007; Gonzalez et al., 2010, 2015). To assess modeled forest AGB dynamics at the pixel scale, which can clearly indicate error sources and their contribution rates, we applied a Monte Carlo analysis.

The specific objectives of our study were as follows: (i) to explore an effective method for estimating regional forest AGB using high-dimensional, remotely sensed information; (ii) to strengthen the robustness, generality, and applicability of the process-based ecological model for obtaining reliable forest carbon fluxes; (iii) to model continuous forest AGB dynamics at a fine spatio-temporal scale through the innovative and consistent integration of AGB with carbon fluxes; and (iv) to quantitatively assess the uncertainty of modeled forest dynamics at the pixel scale.

2. The study area and observations

2.1. The study area

The Heihe River Basin (HRB), one of the largest and most important inland river basins in the arid region of northwestern China, is composed of the following three major geomorphic components: (i) the southern Qilian Mountains, (ii) the middle Hexi Corridor, and (iii) the northern Alxa Highland. The landscapes are diverse and include glaciers, frozen soils, alpine meadows, forests, irrigated crops, riparian ecosystems, and deserts (Fig. 1) (Li et al., 2009). The Qilian Mountains (the conserved forested area) were selected as our study area because they are the source of water that sustains both natural ecosystems and ~500,000 people within the large oasis (Li et al., 2013).

The Qilian Mountains span an area of 10,400 km^2 and consist of 72% alps, 27% fluvial areas, and 1% oasis with elevations ranging from 1500 to 6000 m above sea level. The area has a typical temperate continental mountainous climate. The diurnal difference in temperature is dramatic and precipitation largely occurs during the summer (with annual rates of 350–495 mm). Dominant vegetation includes mountainous pastures, shrubs, and forests. Forests, mainly composed of *Picea crassifolia* mixed with a small fraction of *Sabina przewalskii*, only survive on shady slopes (from altitudes of 25003300 m) while sparse grass inhabits sunlit slopes.

2.2. Observations and the study data

A portion of the measurements employed in this study was collected under the framework of Water Allied Telemetry Experimental Research (WATER), a multi-scale and simultaneous airborne, spaceborne, and