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Estimating forest carbon fluxes for large regions based on process-based modelling, NFI data and Landsat satellite images

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ABSTRACT

The aim of this study was to develop and evaluate a new approach for estimating forest carbon fluxes for large regions based on climate-sensitive process-based model, national forest inventory (NFI) data and satellite images. The approach was tested for Central Finland and Lapland with NFI field data and daily weather data from 2004 to 2008.

The approach combines (1) a light use efficiency (LUE) model, (2) a process-based summary model for estimating gross primary production (GPP) and net primary production (NPP), and (3) the Yasso07 soil carbon model, which together allow the estimation of net ecosystem exchange (NEE). Landsat TM 5 satellite images were utilized to generalize the carbon fluxes obtained for field sample plots for all forested areas using the *k*-NN imputation method. The accuracy of the imputations was examined by leave-one-out cross validation and by comparing the imputed and simulated values with Eddy covariance (EC) measurements.

RMSE of the *k*-NN imputations was slightly better in Central Finland than in Lapland, the bias staying at a similar level. Based on the EC comparisons, the approach seemed to work rather well with GPP estimates in both areas, but in the north the NEE estimates were remarkably biased. The main advantages of the approach include its applicability to basic NFI data and a high output resolution (30 m).

The method proved to be a promising way to produce carbon flux estimates based on large-scale forest inventory data and could therefore be easily applied to the whole of Northern Europe. However, there are still drawbacks to the approach, such as lacking parameters for peat lands. One of the future goals is to integrate the approach with an interactive mapping framework, which could thereafter be utilized, for example, in climate change research.

1. Introduction

When estimating forest growth in changing climate, for example in increasing temperature and atmospheric CO_2, climate-sensitive process-based forest growth models offer an alternative tool to traditional empirical growth models, which rely on the data measured in the past (Mäkelä et al., 2000). Process-based models are able to produce carbon flux estimates, such as gross primary production (GPP), net primary production (NPP), and the whole net ecosystem exchange (NEE). For this reason, they can be utilized, for example, for analysing what kind of forests tend to be carbon sinks and which of those are carbon sources, and how the carbon balance changes when either the climate or forest management regimes change. Therefore, utilizing process-based growth models can offer essential benefits for both environment and industry related decision making and for developing climate policies in the current situation.

Process-based models have often been criticized for being too complex to use and too difficult to parameterize; therefore, they have rarely been utilized in practical applications (Mäkelä et al., 2000; Peng et al., 2002; Matala et al., 2006). Hybrid and summary models may offer solutions to the problem. Hybrid models are combinations of empirical and process-based models, still functioning with a realistic amount of input data, and flexible under changing environmental conditions (for example, Landsberg, 2003; Valentine and Mäkelä, 2005; Nuutinen et al., 2006; Matala et al., 2006; Peng et al., 2002). On the contrary, summary models are simplifications of more complex process-based models, such as the 3-PG model by Landsberg and Waring (1997), which is a simplification of FOREST-BGC by Running (1994), and the pipe-model simplification by Härkönen et al. (2010), which is

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based on the PipeQual model (Mäkelä and Mäkinen 2003; Kantola et al. 2007). The main advantages of the summary models are that they function based on tree physiology and climate input – yet having a simple model structure – and that the amount of required input data and the number of parameters can be maintained at a realistic level.

In most developed countries, national forest inventory and weather stations cover the whole country, which allows applying simplified process-based models to produce carbon flux estimations in a large network of sample plots. By combining the plot wise estimations with remote sensing data, such as satellite images, it is possible to extend predictions to areas where input data are not available, as the values of the image bands are proportional to green leaf biomass, and further to photosynthesis (Rautiainen et al., 2010). Stand properties can be generalized, for example, by using the *k* nearest neighbour (*k*-NN) imputation, which has been successful in estimating traditional forest characteristics, such as height, diameter, basal area, or volume, based on either remote sensing data (for example, Tomppo, 1990) or sample tree measurements (Korhonen and Kangas, 1997; Sironen, 2009). There are also studies that introduce *k*-NN methods for estimation of, for instance, forest biomasses based on satellite images (Muukkonen and Heiskanen, 2007; Tuominen et al., 2010) and carbon pools (Dong et al., 2003). These kind of ecological remote sensing map products offer versatile possibilities for further utilization in research, forest planning, and policy making efforts; for example, by using them as input data for ecological models in order to make area-level predictions. For example, MODIS (Moderate Resolution Imaging Spectroradiometer) thematic maps are freely available for numerous different environmental variables, such as leaf area index, land cover, and land surface temperature, and they have been widely utilized in recent studies both as input data for growth models and for evaluation purposes (Zhao et al., 2005; White et al., 2006; Coops et al., 2007). MODIS also offers NPP maps, which have been developed by utilizing an Eddy covariance (EC) network and process-based models (Running et al., 2004). The disadvantage of the MODIS product, however, is its coarse resolution (1 km). Further, the EC based products are based on a limited network of ground data, due to a sparse Eddy flux network (Turner et al., 2006).

In this study, we introduce and validate a method for generalizing carbon fluxes with *k*-NN imputation for large areas based on a dense grid of carbon flux simulations and Landsat 5 TM satellite images, resulting in carbon flux maps with a 30 m resolution. We assumed that forest GPP, NPP, and NEE can be estimated based on a structural equality in areas where there is little climatic and species variation as inferred from Landsat TM images. Annual carbon fluxes (GPP, NPP, NEE) were estimated for 2004–2008 using daily weather data and a process-based growth model chain tailored for the NFI based sample plot data. Varying numbers of nearest neighbours and different sets of satellite image channels were tested, and a leave-one-out cross validation was used for examining the accuracy of the imputation. The imputed GPP and NEE values were compared with corresponding values from EC towers located in Sodankylä in Lapland and Hyytiälä in Southern Finland. The Sodankylä and Hyytiälä results were also compared with results from direct simulations with the EC sites' stand data.

2. Materials and methods

2.1. Field data

The field data comprised of the Finnish National Forest Inventory (NFI) data for Central Finland and Lapland measured during 2004–2008. A total of 1072 sample plots from Central Finland and 365 plots from Lapland were included in the analysis. For selection, the plots had to match the following criteria: the plot had to be on a mineral soil, the whole plot had to consist of only a single stand, and it had to be located in the selected Landsat image (Fig. 1).

The type of sample plot employed in the NFI is a truncated angle-gauge plot, and the maximum radius of the plots was 12.52 m in Central Finland and 12.45 in Lapland (see Tomppo, 2006). The plots were located systematically in clusters, each cluster containing 18 plots in Central Finland and 14 plots in Lapland. The distance between the plots within a cluster was 300 m, and the distance between the clusters was 6–8 km and 6–11 km in Central Finland and Lapland, respectively. The tally trees were selected with a relascope coefficient of 2 in Southern Finland and 1.5 in Lapland. Every 7th tree over the whole inventory area was measured as a sample tree. Diameter and tree species were collected from the tally trees, whereas total tree heights and heights to the live crown base were only measured for the sample trees.

The generalization of the aforementioned sample tree characteristics over the tally trees was implemented using a multivariate linear mixed-effects model with species-specific parameters designed for multi-response NFI data (Eerikäinen, 2009). The fixed parts of the two linear models of the simultaneous system for total height and crown ratio, i.e., the ratio of live crown length to tree height, consisted of both tree and stand-level independent variables such as diameter at breast height, measurable stand characteristics and site quality indicators. Due to the hierarchically correlated data (clusters – forest stands – sample trees), the intercepts and the slopes (i.e. the coefficients associated with tree

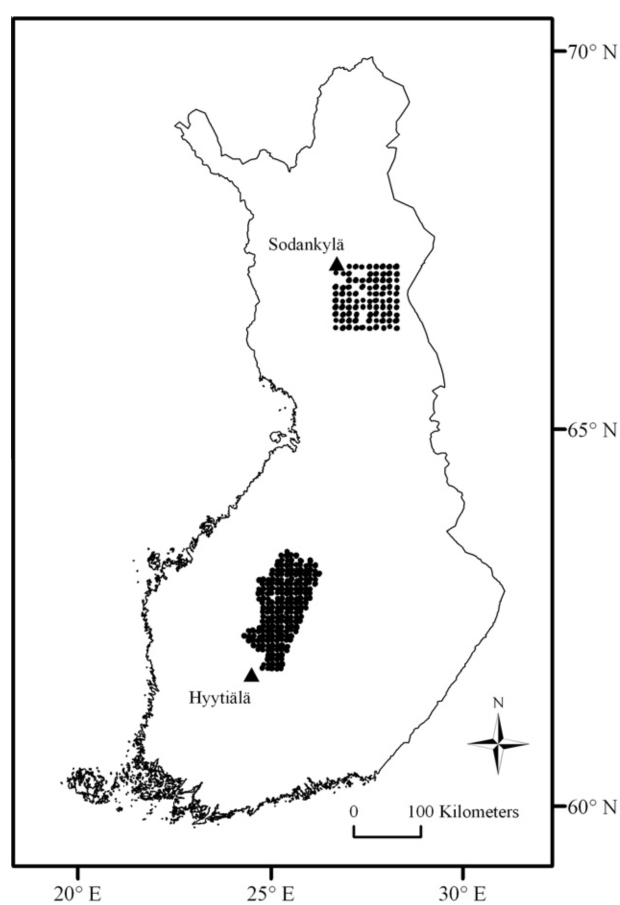

Fig. 1. Location of the NFI sites (grey dots) and Eddy flux sites (black triangles) included in the study.