Remote Sensing of Environment 141 (2014) 90–104

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Estimating landscape net ecosystem exchange at high spatial–temporal resolution based on Landsat data, an improved upscaling model framework, and eddy covariance flux measurements

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ARTICLE INFO

Article history:
Received 10 April 2013
Received in revised form 24 October 2013
Accepted 26 October 2013
Available online 22 November 2013

Keywords:
Net ecosystem exchange
Eddy-covariance
Regression tree
Image fusion
Footprint climatology
Upscaling

ABSTRACT

More accurate estimation of the carbon dioxide flux depends on the improved scientific understanding of the terrestrial carbon cycle. Remote-sensing-based approaches to continental-scale estimation of net ecosystem exchange (NEE) have been developed but coarse spatial resolution is a source of errors. Here we demonstrate a satellite-based method of estimating NEE using Landsat TM/ETM + data and an upscaling framework. The upscaling framework contains flux-footprint climatology modeling, modified regression tree (MRT) analysis and image fusion. By scaling NEE measured at flux towers to landscape and regional scales, this satellite-based method can improve NEE estimation at high spatial-temporal resolution at the landscape scale relative to methods based on MODIS data with coarser spatial–temporal resolution. This method was applied to sixteen flux sites from the Canadian Carbon Program and AmeriFlux networks located in North America, covering forest, grass, and cropland biomes. Compared to a similar method using MODIS data, our estimation is more effective for diagnosing landscape NEE with the same temporal resolution and higher spatial resolution (30 m versus 1 km) ($r^2 = 0.7548$ vs. 0.5868, RMSE = 1.3979 vs. 1.7497 g C m^{-2} day^{-1}, average error = 0.8950 vs. 1.0178 g C m^{-2} day^{-1}, relative error = 0.47 vs. 0.54 for fused Landsat and MODIS imagery, respectively). We also compared the regional NEE estimations using Carbon Tracker, our method and eddy-covariance observations. This study demonstrates that the data-driven satellite-based NEE diagnosed model can be used to upscale eddy-flux observations to landscape scales with high spatial–temporal resolutions.

1. Introduction

A number of different methods have been developed to estimate net ecosystem carbon exchange (NEE), which can be classified as top-down or bottom-up approaches. Under some pieces of constraining information, such as regional prior flux estimates (e.g. Gurney et al., 2003) or an imposed error covariance structure (e.g. Gourdji, Mueller, Schaefer, & Michalak, 2008; Michalak, Bruhwiler, & Tans, 2004; Mueller, Gourdji, & Michalak, 2008), the top-down approaches are based on atmospheric CO_2 concentration measurements and inverse modeling (Ciais et al., 2010; Deng et al., 2007; Gurney, Baker, Rayner, & Denning, 2002, 2008, Gurney et al., 2002; Hayes et al., 2012; Peters et al., 2010) to estimate the surface emissions given observed fields of atmospheric CO_2 concentration, wind speed and wind direction. The bottom-up approaches use

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http://dx.doi.org/10.1016/j.rse.2013.10.029

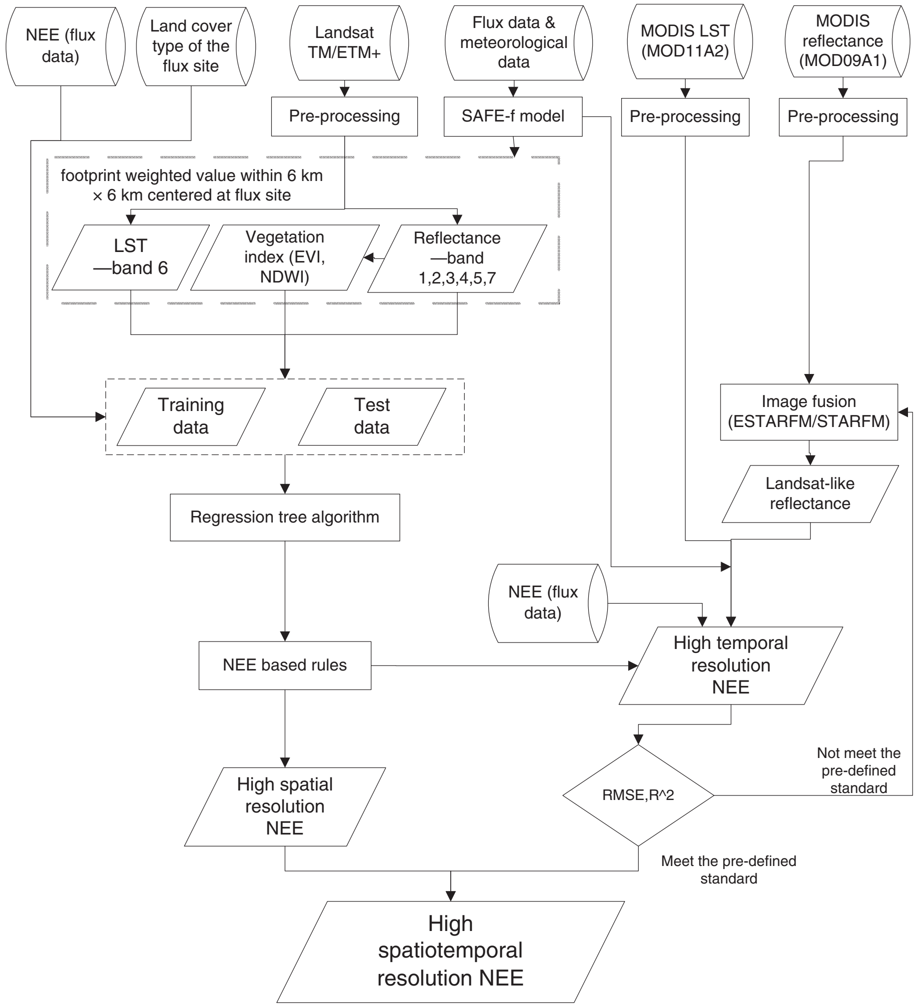

Fig. 1. The flowchart of landscape NEE estimation algorithm.

observations of the surface properties to resolve CO_2 emission rates, including using emission models based on observations from eddy-covariance (EC) flux-towers, biomass inventories (Peylin et al., 2005; Stinson et al., 2011), terrestrial biosphere models (Hayes et al., 2012; Keenan, Baker, et al., 2012) and remote sensing data products (Churkina, Schimel, Braswell, & Xiao, 2005; Xiao, Zhuang, et al., 2011; Xiao et al., 2008). Progress in estimating carbon fluxes has been achieved at either the large, continental scale(Gurney et al., 2002, 2008) or the local, ecosystem scale (typically less than 1–3 km^2 for each site) (Chen et al., 2012). However, the landscape-scale (10^1–10^2 km^2) carbon flux and especially its spatial–temporal variations remain poorly modeled (Chen, Chen, Mo, Black, & Worthy, 2008; Cook et al., 2004; Piao et al., 2009). Accurate quantification of the NEE dynamics at the landscape and regional scales is comparatively weak and achieving greater accuracy and precision of modeling at this level are crucial to improving our understanding of the terrestrial carbon cycle locally and for reducing global carbon budget errors (Keenan, Davidson, Moffat, Munger, & Richardson, 2012; Tang et al., 2012; Xiao, Chen, Davis, & Reichstein, 2012; Xiao, Davis, Urban, Keller, & Saliendra, 2011; Xiao, Zhuang, et al., 2011; Xiao et al., 2008).

Remote-sensing-based methods have the potential to scale the EC measurement of NEE to larger spatial scales. Unlike other bottom-up methods, remote-sensing-based approaches are not limited by the availability of the in situ ground measurements. Veroustraete, Patyn, and Myneni (1996) combined normalized difference vegetation index (NDVI) and land surface flux data to estimate NEE using an ecosystem model. Maselli, Chiesi, Fibbi, and Moriondo (2008) and Maselli et al. (2010) combined aircraft EC flux data, remote-sensing-based and process-based ecosystem models to estimate NEE at different spatial–temporal scales. Mahadevan et al. (2008) used a satellite-based assimilation scheme to estimate NEE based on vegetation indices derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data, climate data and tower EC flux data. Xiao et al. (2008), Xiao, Zhuang, et al. (2011) estimated NEE at 1-km and 8-day resolutions over the conterminous United States by combining MODIS imagery and tower EC flux data from the AmeriFlux database using the modified regression tree (MRT) method. To our knowledge, there has been no such published study estimating landscape-scale NEE with high spatial (less than 100 m) and high temporal resolutions by making use of available global EC flux data and remote sensing imagery.

In this study, we developed an integrated method to estimate NEE at landscape scales with high spatial resolution (30 m) by synthesizing EC flux measurements with remotely-sensed data to account for the land surface heterogeneity. This approach combines an enhanced spatial and temporal adaptive reflectance fusion model (ESTARFM, Zhu, Chen, Gao, Chen, & Masek, 2010), a Simple Analytical Footprint model on Eulerian coordinates (SAFE-f, Chen, Black, Coops, Hilker, et al., 2009; Chen et al., 2010, 2012) and the MRT method.

This approach employs these assumptions: i) only the target land-cover type observed by the flux tower (of which the flux footprint is typically less than 1–3 km^2, Chen et al., 2010) is taken as the contribution of observed carbon flux and selected for upscaling using a footprint model, ii) the variation of phenology and the difference between the nearest available Landsat surface reflectance data and the corresponding MODIS