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Modeling terrestrial ecosystem productivity of an estuarine ecosystem in the Sundarban Biosphere Region, India using seven ecosystem models

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ABSTRACT

The net primary production (NPP) is a key indicator for assessing the terrestrial carbon pools and fluxes from the atmosphere to biosphere in any given ecosystem. Adequate measurement of the sensitivity and uncertainty of regional and global carbon pools and fluxes in different climatic and anthropogenic regimes is needed to properly investigate the terrestrial carbon balance. Remote sensing light use efficiency (LUE) approaches can be used to quantify the terrestrial NPP accurately. Using LUE models, NPP was calculated for last two decades of an estuarine ecosystem, the Sundarban Biosphere region, India. Results from seven LUE models: Carnegie-Ames-Stanford Approach (CASA), Global Production Efficiency Model (GLO-PEM), Vegetation Photosynthesis Model (VPM), Eddy Covariance-Light Use Efficiency (EC-LUE), MODerate resolution Imaging Spectroradiometer (MOD17), Temperature and Greenness (TG), Greenness and Radiation (GR) models were compared to ascertain model consistency for NPP estimation during the study period 2000–2013. To optimize structural biases in the model accurate parameterization and systematic multi-method assessment were employed. The influence of the input drivers (biophysical, bioclimatic and environmental stress) on model performances was evaluated. Best model performances were observed over cropland, followed by mixed forest and mangrove ecoregion, respectively. Amongst all model, EC-LUE simulated higher NPP at mangrove ecoregion, while the MOD17 model simulated lower NPP in most of the evaluated biomes. In addition, TG and GR models exhibited larger unexplained variances and found statistically significant at mixed forest site. This error was attributed to the absence of environmental stress factors used to drive these model. GLO-PEM and VPM corroborate with NPP prediction among all LUE models. All seven LUE models predict the statistically significant NPP across the biomes and, the poor model performance is attributed to the different parameterization scheme executed for defining the biophysical and stress variables. Biophysical drivers mostly controlled the model performances, followed by environmental stress and bioclimatic drivers, respectively. This analysis is suggesting that the TG and GR model (driven only by the biophysical factors) could be useful in NPP predictions in the regions with no meteorological inputs and real-time eddy covariance flux tower measurement.

1. Introduction

Terrestrial net primary production (NPP), defined as the sum of photosynthetic carbon uptake by a green canopy, plays a significant role in the global and regional carbon cycle dynamics and aids in understanding the nature of carbon stability in an ecosystem (Zhang et al., 2015). NPP is a key component of carbon biogeochemical cycle that links atmospheric CO_2 and terrestrial ecosystem and helps to determine the anthropogenic controls over the environment (Ruimy et al., 1996; Dong et al., 2012; Liu et al., 2014; Canu et al., 2015). The global carbon fluxes from the atmosphere to the biosphere are the major contributor for NPP as compared to any other fluxes (Hazarika et al., 2005). The model estimation of global NPP varies within 40–80 PgC year^{-1} has clearly shown the uncertainty in the estimate of spatiotemporal NPP (Crammer et al., 1999). Thus, the focal point are the three-core elements (1) spatial resolution (2) land cover, and (3) light use efficiency (LUE) for accurate quantification of terrestrial NPP using remote sensing LUE approach (Hunt et al., 1996; Running et al., 1999a,b; Ahl et al., 2005). Direct measurement of carbon fluxes from atmosphere to biosphere is challenging, and as such, a number of remote sensing approaches have developed in the last few decades with the primary aim to accurately estimate and predict regional and global NPP (Canadell

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et al., 2000; Ogutu et al., 2013; Zhang et al., 2015). Therefore, accurate quantification of terrestrial NPP using different LUE models are essential for (1) analysing spatial and temporal changes of carbon stock density; (2) evaluating the spatiotemporal variability of forest dynamics and its relationship with global and regional NPP; (3) data for model based global and regional carbon and biomass change assessment (e.g. Tang et al., 2010; Yan et al., 2011; Yuan et al., 2014a,b).

Several LUE models have been developed in the last two decades to deal with the uncertainty of accounting global and regional NPP over varied ecoregions across the world (Lieth and Whittaker, 1975; Potter et al., 1993; Field et al., 1995; Ruimy et al., 1996, 1994; Running et al., 2004; Xiao et al., 2004, 2007; Yuan et al., 2014a,b). However, the structural differences between the estimated magnitude and spatiotemporal distribution of NPP have substantially persisted in different LUE models (Yuan et al., 2014a,b). Ruimy et al. (1994) defines three different types of models to quantify spatiotemporal NPP viz. statistical models, parametric model, and process-based models. Statistical models like Miami model (Leith, 1972) and Montreal Model (Leith and Box, 1972) correlates NPP with the meteorological parameters and evapotranspiration through linear and nonlinear approximation. Parametric models estimate NPP from the incident radiation use and absorption efficiency by plant canopies viz. Carnegie-Ames-Stanford-Approach (CASA) model (Potter et al., 1993); Eddy Covariance – Light Use Efficiency (EC-LUE) model (Yuan et al., 2007); Vegetation Photosynthesis Model (VPM) (Xiao et al., 2004); CENTURY model (Parton et al., 1996); C-Fix model (Veroustraete et al., 2002); Global Production Efficiency Model (GLO-PEM) (Prince and Goward et al., 1995). The process-based models works on the LUE approach and are widely used for calculating terrestrial NPP across the biomes (Amthor et al., 2001; Rui et al., 2002; Ogutu et al., 2013) e.g. BIOME-BGC model (Running and Coughlan, 1988), MODerate resolution Imaging Spectroradiometer (MOD17) model (Running et al., 2004; Liu et al., 1997).

During the last few decades, several approaches were introduced for biome specific modeling of terrestrial ecosystem productivity at any ecosystem scale (Monteith, 1977). In direct comparison approach, mathematical formulation of each model treated as control variables which significantly alter the amplitude of model performances in various experimental setup (Adams et al., 2004). However, this approach found to be inappropriate in a more complex ecosystem (terrestrial ecosystem) (Wang et al., 2011; Ogutu et al., 2013). In production efficiency approach, a constant light use conversion has been observed over the various environmental condition to assimilate dry carbon (Running et al., 2004), which seems to have decreased as of increasing biomass and temperature (Ruimy et al., 1996). A radiative transfer approach has been developed and followed out to estimate satellite derived leaf area index (LAI) (Hazarika et al., 2005). In multimodel ensembles (MME) approach, numerical formulations of process-based models are taken into consideration to run a group of models with the same input approximation and boundary/layer condition within the robust experimental setup. The mean output of the ensembles models are then analyzed, and the simulated variance between each model treated as the model's structural uncertainty (Tebaldi and Knutti, 2007; Wang et al., 2011; Ogutu et al., 2013).

Remote sensing LUE models could accurately estimate the spatiotemporal NPP over diverse ecosystems (Higuchi et al., 2005; Ichii et al., 2005). Seven different LUE-based models: CASA, EC-LUE, GLO-PEM, VPM, MOD17, Temperature and Greenness (TG) model, and Greenness and Radiation (GR) model have been employed in this study to estimate spatiotemporal NPP. However, several earlier studies have shown the uncertainty in estimating NPP and gross primary production (GPP) in major ecosystem types (Cramer et al., 1999; Yuan et al., 2007; Huntzinger et al., 2012; Raczka et al., 2013; Yuan et al., 2014a,b). Moreover, a comparison study between the 17 ecosystem models had revealed the unsteadiness in simulating global NPP as the lowest global NPP (39.9 Pg C yr^{-1}) was almost 50% smaller than the maximum estimate (80.5 Pg C yr^{-1}) (Cramer et al., 1999; Yuan et al., 2014a,b). Yuan et al. (2014) indicated that the individual model prediction, validations and accuracy assessments are insufficient to identify the sources of the wide range of model differences. Additionally, it is essential to conduct rigorous comparison studies in a standardized framework with consistent validation datasets and driving variables to assess the model sensitivity in varied climatic and environmental scenarios for enhancing model performances. Therefore, to achieve accurate estimates of vegetation production dynamics, it is necessary to compare the performances of LUE models and compare them against consistent and extensive measurements that are available (Yuan et al., 2014a,b).

The purpose of the present work is to examine the consistency and uncertainty in estimating terrestrial ecosystem productivity through LUE models in Sundarban Biosphere Region, India with the support of satellite imagery and meteorological inputs. The estimated NPP further validated with the ground based measurements and multimodel evaluation. Remote sensing satellite products were mostly used in this study for being the easy availability and accessibility of the data. Therefore the specific objectives of this research are to (1) evaluate model performances across the varied ecoregions, and (2) investigate the impact of biophysical, bioclimatic and environmental stress drivers on the seven LUE models.

2. Materials and methods

2.1. Study area

The study area consisted of two districts of the state of West Bengal, India including the Indian part of Sundarban. This area was further subdivided into four broad subdivisions; i.e. core zone which covers 1700 km^2, a development zone that covers 5300 km^2, a manipulation region which covers 2400 km^2, and the restoration zone which covers up to 230 km^2 (Nandy and Kushwaha, 2010). The Sundarban mangrove area has been declared "World Heritage Site" by the International Union for Conservation of Nature (IUCN) in 1987 and was declared as a "Biosphere Reserve" zone by United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1997 (Datta and Deb, 2012). The Indian part of Sundarban is comprised of 108 small islands among which 54 are suitable for human habitation. Among the 87 plant species documented, 37 are categorised as true mangroves where, the dominants species are *Heritiera fomes, Heritiera littoralis, Avicennia marina* and 186 bird species out of a total of 1287 different animal species (West Bengal Forest Department, 2007). The region comprises of different land cover, mangrove ecosystem with tidal creek and estuary in the southern part, a built-up urban area in the east and extensively cultivated land in the middle and western parts of the region (Mukherjee et al., 2013). The terrain range is not pronounced clearly; elevation ranges from 0 to 100 m in this region. The local climate is characterized by a sharp temperature and precipitation difference, which ranges from 41 °C in May (max) to 10 °C in January (min) and 1500–2100 mm respectively (Indian Meteorological Department, India). The annual solar radiation ranges from 6500 to 7500 MJ m^{-2} $year^{-1}$. The physiognomies are varied and complex, including plain, estuary, tidal flat, tidal forest, riverine land, etc. Major soil types are very deep poorly drained loamy soil, poorly drained fine soil, sandy, clay loam (National Bureau of Soil Survey & Land Use Planning (NBSS & LUP, Govt. of West Bengal, India) (Fig. 1).