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Modeling gross primary production of paddy rice cropland through analyses of data from CO_2 eddy flux tower sites and MODIS images

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ABSTRACT

Accurate information on the gross primary production (GPP) of paddy rice cropland is critical for assessing and monitoring rice growing conditions. The eddy co-variance technique was used to measure net ecosystem exchange (NEE) of CO_2 between paddy rice croplands and the atmosphere, and the resultant NEE data then partitioned into GPP (GPP_{EC}) and ecosystem respiration. In this study, we first used the GPP_{EC} data from four paddy rice flux tower sites in South Korea, Japan and the USA to evaluate the biophysical performance of three vegetation indices: Normalized Difference Vegetation Index (NDVI); Enhanced Vegetation Index (EVI), and Land Surface Water Index (LSWI) in terms of phenology (crop growing seasons) and GPP_{EC}, which are derived from images taken by Moderate Resolution Imaging Spectroradiometer (MODIS) sensors. We also ran the Vegetation Photosynthesis Model (VPM), which is driven by EVI, LSWI, photosynthetically active radiation (PAR) and air temperature, to estimate GPP over multiple years at these four sites (GPP_{VPM}). The 14 site-years of simulations show that the seasonal dynamics of GPP_{VPM} successfully tracked the seasonal dynamics of GPP_{EC} ($R^2 > 0.88$ or higher). The cross-site comparison also shows that GPP_{VPM} agreed reasonably well with the variations of GPP_{EC} across both years and sites. The simulation results clearly demonstrate the potential of the VPM model and MODIS images for estimating GPP of paddy rice croplands in the monsoon climates of South Korea and Japan and the Mediterranean climate in California, USA. The application of VPM to regional simulations in the near future may provide crucial GPP data to support the studies of food security and cropland carbon cycle around the world.

1. Introduction

Paddy rice is a very important grain crop, comprising about 163 million ha worldwide in 2014 – an 11% increase over the past ten years (FAOSTAT, 2015). Asia provides the world's largest rice area and production, accounting for approximately 88% of the globally harvested rice area and 91% of the global rice production in 2014 (FAOSTAT, 2015). Seasonally flooded paddy rice fields are a major source of methane emissions (in the range of 31–112 Tg yr^{-1}), amounting to 12–26% of the anthropogenic CH_4 release (Gutierrez et al., 2013; Ly et al., 2013; Tokida et al., 2010) and contributing about 11% of the total methane flux to the atmosphere (Allen et al., 2003; Dentener and Raes, 2002; Li et al., 2005; Prather and Ehhalt, 2001). Although several *in-situ* studies reported that paddy rice fields had high soil carbon sequestration and acted as net sinks for CO_2 (Bhattacharyya et al., 2014; Kell, 2012; Liu et al., 2013; Mandal et al., 2007; Pan et al., 2004; Zhang et al., 2014), there are very limited knowledge and large uncertainty about the carbon fluxes of paddy rice fields. Therefore, it is important to measure and model the carbon fluxes of paddy rice fields, including the net ecosystem exchange (NEE) of CO_2 between paddy rice fields and the

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atmosphere, gross primary production (GPP), and ecosystem respiration (ER) across the diverse climate, soils and crop production systems.

The eddy covariance (EC) technique has been used to measure the net ecosystem exchange of CO_2 between the land surface and the atmosphere over various biomes, and the observed NEE data then partitioned into GPP and ER (Baldocchi et al., 2001). The observed NEE data and derived GPP and ER data from CO_2 flux tower sites have been widely used to support model development and satellite remote sensing across local, regional and global scales (Mahadevan et al., 2008; Running et al., 1999; Stockli et al., 2008; Williams et al., 2009). Out of hundreds of CO_2 eddy flux tower sites in operation, however, there are only a few CO_2 flux tower sites that measure carbon fluxes over paddy rice ecosystems (Alberto et al., 2012; Alberto et al., 2009; Baldocchi et al., 2001; Bhattacharyya et al., 2013; Chen et al., 2015; Hatala et al., 2012; Hossen et al., 2012; Knox et al., 2015; Matthes et al., 2015; Mizoguchi et al., 2009; Ono et al., 2015; Ren et al., 2007; Rossini et al., 2010; Saito et al., 2005; Yang et al., 2016).

Remote sensing provides another viable way to measure the structure and function of terrestrial ecosystems and scale-up carbon fluxes from local to regional and global scales. A number of light (radiation) use efficiency (LUE) models, sometimes called production efficiency models (PEM), have been developed to estimate GPP of terrestrial ecosystems, driven by vegetation indices (VI) derived from optical images and climate data (Barton and North, 2001; Brogaard et al., 2005; Machwitz et al., 2015; Nichol et al., 2000; Seaquist et al., 2003; Yuan et al., 2007). These models estimate GPP as a product of absorbed photosynthetically active radiation (APAR) and light use efficiency (ε) ($GPP = APAR \times \varepsilon$) and can be divided into two groups depending on their approaches to estimate APAR (Dong et al., 2015). One group of LUE models uses the fraction of photosynthetically active radiation (PAR) absorbed by the vegetation canopy ($FPAR_{canopy}$) to estimate $APAR_{canopy}$ ($APAR_{canopy} = PAR \times FPAR_{canopy}$), including the Global Production Efficiency Model (GloPEM) (Prince, 1995), Carnegie-Ames-Stanford Approach (CASA) model (Potter, 1999; Potter et al., 1993), and Photosynthesis (PSN) model (Running et al., 2000; Zhao et al., 2005). The other group of LUE models uses the fraction of PAR absorbed by chlorophyll or green leaves ($FPAR_{chl}$ or $FPAR_{green}$) to estimate $APAR_{chl}$ ($APAR_{chl} = PAR \times FPAR_{chl}$) (Gitelson et al., 2006; Sims et al., 2006; Wu et al., 2010; Xiao et al., 2004b; Zhang et al., 2013; Zhang et al., 2009; Zhang et al., 2006). The Vegetation Photosynthesis Model (VPM) is the first GPP model that uses $FPAR_{chl}$ concept to estimate $APAR_{chl}$ and GPP (Xiao et al., 2004a). The VPM model has been applied to estimate GPP over a variety of CO_2 flux tower sites, including forests (temperate deciduous broadleaf forest, evergreen coniferous forest, seasonally moist tropical forest) (Xiao et al., 2004a; Xiao et al., 2004b; Xiao et al., 2005a; Xiao et al., 2005b), savannas(Jin et al., 2013), grasslands (Li et al., 2007; Wagle et al., 2014; Wu et al., 2008), upland crops (maize, winter wheat, soybean) (Kalfas et al., 2011; Wang et al., 2010), and freshwater inland wetlands (Kang et al., 2014b). However, it has not yet been applied to estimate GPP of paddy rice fields. Given the important role of paddy rice fields in food security, climate and hydrology, individual site verification of the VPM model is critical prior to its usage at the regional and global scales.

The objectives of this study are twofold: (1) to evaluate the biophysical performance of vegetation indices in paddy rice fields, including Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI) and Land Surface Water Index (LSWI); and (2) to apply and assess the VPM estimates of GPP of paddy rice fields over multiple years. Based on the availability of in-situ data from CO_2 eddy flux tower sites, we selected two paddy rice sites in South Korea, one site in Japan, and one site in California, USA. These four sites represent two different climate systems (monsoon climate in eastern Asia and Mediterranean climate in California) and cropping practices (single paddy rice crop, barley-rice double cropping rotation in a year, and a mix of paddy rice and natural wetlands). The results of this work may offer significant contribution to the improvement of GPP models and our long-term capacity for monitoring the paddy rice agriculture that feeds >50% of the world's human population.

2. Materials and methods

2.1. Description of the study sites

In this study we selected four paddy rice flux tower sites (Table 1): Gimje site and KoFlux Haenam site in South Korea, Mase site in Japan, and the Twitchell Island site in California, USA (Fig. 1). Detailed descriptions of these four sites can be obtained via the websites for AmeriFlux (http://ameriflux-data.lbl.gov:8080/SitePages/siteInfo.aspx?US-Twt) and AsiaFlux (http://asiaflux.net/?page_id=22). The flux footprint analysis of the four flux tower sites can be found in the Supplementary Information SI. Here we provide a brief description of these sites (Table 1).

2.1.1. The Gimje paddy rice site in South Korea (GRK)

The GRK site (35.7451°N, 126.8524°E) is located in the southwestern coastal zone of South Korea, where barley and paddy rice double cropping practices are widely distributed. The flux tower's surrounding area is flat with an elevation of approximately 21 m above sea level; soil types at the site are silt loam. On average, the annual mean air temperature is 12.9 °C and annual precipitation is 1253 mm. The site rotates barley and paddy rice each year: barley is planted in late October of the previous year and harvested in early June, and then rice plants are transplanted in June and harvested in October(Min et al., 2014; Min et al., 2013; Shim et al., 2015).

2.1.2. The Haenam paddy rice site in South Korea (HFK)

The HFK site (34.5538°N, 126.5699°E) is located near the southwestern coastal zone of South Korea, where a variety of land cover types exist, including rice paddies (Kwon et al., 2010; Kwon et al., 2009). The terrain is relatively flat with an elevation of 13.7 m above sea level. On average, the annual mean air temperature is 13.3 °C and annual precipitation is 1306 mm (Ryu et al., 2008). Soil types at the site vary from silt loam to loam. The site has a two-crop rotation (other crop-rice) in a year. The fields are flooded in late May, and rice plants transplanted in early-July and harvested in late-September or early October.

2.1.3. The MASE paddy rice site in Japan (MSE)

The Mase paddy rice site (36.0539°N, 140.0269°E) is located in a rural area of Tsukuba city in central Japan, about 50-km northeast of Tokyo (Saito et al., 2005). The climate is warm and humid. The study site is within irrigated flat rice fields extending 1.5 km (north-south) by 1 km (east-west). On average, annual precipitation is approximately 1236 mm, and the annual mean air temperature is 13.5 °C. Local farmers manage the site as a single-rice cropping paddy field; their cropping practice and calendar is representative of the region. The paddy rice field is plowed and flooded in late April, and rice plant transplanting occurs in early May. Rice plants are harvested in early or mid-September.

2.1.4. The Twitchell island paddy rice site in the USA (TWT)

The Twitchell Island paddy rice site (38.1087°N, 121.6530°W) is owned and managed by the California Department of Water Resources and is within the Sacramento-San Joaquin Delta, approximately 100 km inland from the Pacific Ocean (Knox et al., 2015). Between July 2009 and January 2010, the site was located ~300 m to the South (38.105530°N, 121.652097°W). The region experiences a Mediterranean climate. On average, the annual mean air temperature is 15.6 °C, and annual precipitation is 421 mm. Two varieties of rice were planted from mid-April to May and harvested between late September and October or early November (Hatala et al., 2012; Knox et al., 2016; Knox et al., 2015).