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Research paper

A spatially hierarchical integration of close-range remote sensing, leaf structure and physiology assists in diagnosing spatiotemporal dimensions of field-scale ecosystem photosynthetic productivity

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A B S T R A C T

There are great variations of inter-annual ecosystem photosynthetic productivity (GPP) in rice agricultural mosaic landscapes in Asian monsoon regions, consisting of relatively small land holdings. It is therefore of great importance to capture and interpret spatiotemporal aspects of per-field GPP. This goal, however, remains challenging partially due to absence of adequate methodology that applies ecophysiological data to broader spatial and temporal dimensions to explicitly quantify influences of environment change on per-field GPP. To accomplish the goal, field experiments were carried out at spatially adjacent flooding paddy (PD) and rainfed (RF) lowland rice (*Oryza sativa*) fields, taking year-round measurements in micrometeorological factors, leaf and canopy photosynthesis, and field reflectance with help from an unmanned aviation vehicle (UAV) system. A spatially hierarchical integration (PIXel based CANopy photosynthesis model, PIXCAN) that fuses measurements from leaf to canopy and field scales was then developed. Our results showed that the PIXCAN fusion could well capture and characterize spatial properties of per-field ecosystem GPP. Spatial variations (SV) of ecosystem carbon uptake capacity (GPP_{max}) at the PD and RF fields decreased over the growing season. However, occurrence of prolonged non-precipitation period due to climate anormaly in mid-August led to severe constraints of GPP_{max} and counter-seasonally strengthened SV that would decrease in the RF rice field, primarily due to drought impacts on light-harvesting efficiency and less to stomatal conductance. Collectively, we highlighted ecological implications of the integration applied at field niche in spatially hierarchical observation of ecosystem regulating/production provisions from leaf to landscape dimensions.

1. Introduction

Great fluctuations of inter-annual ecosystem photosynthetic productivity in Asian agroforestry mosaic landscapes are intensively reported by Kwon et al. (2010), Lindner et al. (2015), and Xue et al. (2017a). The observed inter-annual variations of ecosystem photosynthetic productivity are thought to relate to changes in management of multicultural cropping system (i.e. several crops grown in one region in the same year) and changes in phenology of the crops accordingly. Given significantly less amount of water input (Alberto et al., 2013; Thanawong et al., 2014) and marked reduction of greenhouse gas emission as well as global warming potential (Jiang et al., 2016; Tao et al., 2016) in rainfed (RF) rice ecosystems, the RF rice cropping system tends to be the most efficient planting culture among several water-saving field managements (i.e. continuous soil saturation, alternative wet and dry intermittent irrigation). Thereby, its planting area has been rapidly expanded in some regions in Asian monsoon regions, leading to changes in local cropping structure and influencing regional ground-atmosphere interface gas exchange fluxes. Therefore, monitoring of photosynthetic productivity (gross primary productivity, GPP) of multicultural cropping ecosystems on which dry matter production tightly depends and interpretation of their spatiotemporal variations become an important topic.

Increasing knowledge has improved our understanding of hourly and daily GPP rates in flooding paddy (PD) rice ecosystems (Miyata et al., 2000; Campbell et al., 2001; Inoue et al., 2008; Nishimura et al., 2008; Hossen et al., 2011; Hatala et al., 2012; Alberto et al., 2013; Bhattacharyya et al., 2013, 2014; Lee, 2014; Lindner et al., 2015; Vote

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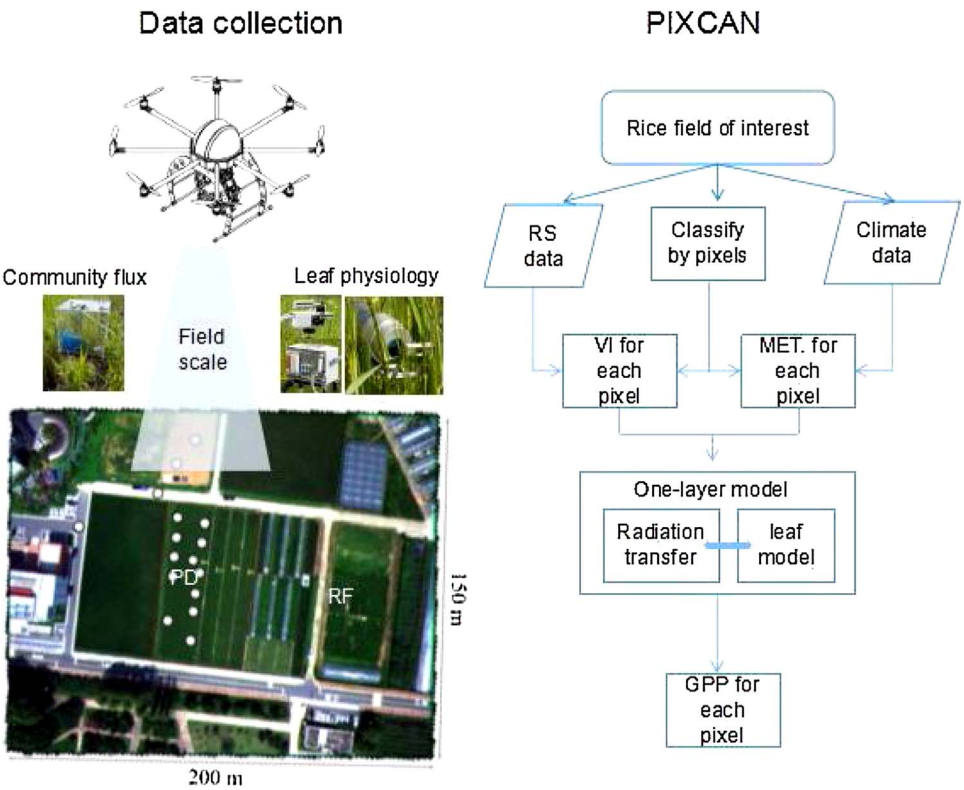

Fig 1. Illustration of field campaign at study site (left-hand panel) and framework of a spatially hierarchical remote sensing network (PIXCAN, right-hand panel) that integrates remote sensing data obtained from an unmanned aviation vehicle (UAV) system and ground surface measurements of leaf structure and function. White plots were established before each UAV flight for measurements of surface reflectance using a hand-held radiometer Cropscan, aiming to make radiometric calibration of UAV imagery. RS: remote sensing; MET.: meteorological data; PIXCAN: PIXel-based CANopy photosynthesis model; VI: vegetation index; GPP: gross photosynthetic productivity.

et al., 2015), so did few studies in the RF lowland rice ecosystems (Alberto et al., 2012; 2013). Newly produced lowland rice planted in rainfed fields could result in relatively high/compatible biomass production without compromising yield in monsoon regions Japan and The Philippines (Alberto et al., 2012; Kato et al., 2006; Katsura et al., 2010). The mean of total growing season photosynthetic productivity (GPP_{total}) in previously reported RF rice ecosystems was 700.4 ± 180.6 g C m^{-2} approximately equal to that of 759.6 ± 50.8 g C m^{-2} in the PD rice ecosystems. Nevertheless, GPP_{total} average in the RF rice ecosystem is featured by large standard deviation/uncertainty. Expansion of rice planting across different geographic sites may exacerbate spatial and temporal variations of regional ecosystem GPP rates.

Correspondingly, one critical question was raised about how water availability (i.e. shifts of cropping culture from the flooding to rainfed) could potentially influence spatiotemporal variations of agroecosystem GPP rates. Interpret great variations in agroecosystem GPP rates via taking into account per-field ecological conditions and their impacts on plant growth and development tends to be necessary. The establishment of new breeding lines that will allow sustainable crop production under rainfed conditions is based on the assumption that long-term evolution has in fact included potentials into the genetic inheritance of rice to cope with marginal oscillations in water supply (Jearakongman et al., 1995). Small differences between the GPP_{total} average in the RF and PD rice ecosystems may imply that regulating mechanisms of photosynthesis in lowland rice planted in upland fields in monsoon regions could be as similar as the PD rice ecosystem.

Traditional physiology analysis showed positive correlation between efficient nitrogen use and photosynthetic productivity in crops (Sinclair and Horie, 1989; Hirel et al., 2001; Xue et al., 2016a). Nitrogen uptake capacity has been proposed as key factor determining plant survival and establishment (Niinemets and Tenhunen, 1997). Effects made to incorporate physiological information into crop growth models have been increasingly concerned (Adiku et al., 2006; Alton, 2017; Rogers et al., 2017), aiming for better predictability of plant characteristics in response to ambient environment changes. However, ground surface measurements using conventional physiology methods are strongly limited to temporal comparisons at individual level, neglecting properties of spatial variation.

To acquire repetitive observations of ecosystem dynamic at spatially broader scale, satellite remote sensing has been well regarded as a powerful measure due to its large swatch area and high repeatability in observation over a growing season. However, observations at spatially coarse resolution technically mask delicate fluctuations of per-field ecological conditions on which plant survival and dispersion depend (Seo et al., 2014). Close-range remote sensing technique that can provide timely temporal information of ecosystem dynamics at finer resolution and at critical growth stages tends to be pragmatically convenient. Recent applications by Zhang and Kovacs (2012) and Ko et al. (2015) in agronomy studies have supported the feasibility of capturing spatiotemporal dimensions of per-field photosynthetic productivity.

In this study, a high-yield lowland rice genotype (*Oryza sativa* L. cv. Unkwang) was planted in two contrasting water regimes, i.e., with flooded paddy and rainfed cropping cultures. Data collection and data analysis were grouped into two categories, depending on spatial scale of data measurements. The first category was referred to intensive gas exchange behavior and crop development that were evaluated over an entire growing season via application of chamber flux measurements at leaf and stand level concurrent with measurements of microclimate, assessments of biomass and nitrogen distribution, monitoring of water status in plant and soil matrix, and estimation of grain yield component.

Escalating approaches are desirable to apply the understanding of plot data that is strongly related to crop carbon and water gas exchange to broader spatial and temporal domains. The second part was posited for spatial integration of canopy leaf and field measurements. Seasonal changes of field spectral reflectance that are strongly associated with canopy biophysical characteristics were monitored using an unmanned aviation vehicle (UAV) system. A data assimilation linking close-range remote sensing products derived from the UAV system with *in situ* measurements of leaf gas exchange was developed to capture and interpret spatiotemporal aspects of ecosystem photosynthetic productivity in the PD and RF rice fields. We highlighted ecological