Remote Sensing of Environment 150 (2014) 82–92

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Estimation of light-use efficiency through a combinational use of the photochemical reflectance index and vapor pressure deficit in an evergreen tropical rainforest at Pasoh, Peninsular Malaysia

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ARTICLE INFO

Article history:
Received 9 May 2013
Received in revised form 16 April 2014
Accepted 18 April 2014
Available online xxxx

Keywords:
lowland dipterocarp forest
phenology
productivity
remote sensing
vegetation index
water conditions

ABSTRACT

In the search for a better method of estimating the light-use efficiency (LUE) of evergreen tropical rainforests, we employed remotely sensed spectral vegetation indices (VIs) to monitor both CO_2 flux and canopy spectral reflectance over 3 years in a lowland dipterocarp forest in Peninsular Malaysia. We investigated the sensitivity of five VIs calculated from spectral reflectance: the photochemical reflectance index (PRI), the canopy chlorophyll index (CCI), the normalized difference vegetation index (NDVI), the enhanced vegetation index (EVI) and the water index (WI).

During the monitoring period, clear seasonal variations were not found in LUE, the observed VIs or the phenological timing (particularly new leaf flush) of dominant dipterocarp trees. Although leaf phenology tended to correlate with variations in the CCI, the highest correlation coefficient among the relationships between LUE and the VIs was observed in PRI ($R = 0.341, n = 699$). Among the relationships between LUE and meteorological factors, the strongest correlation was found between LUE and vapor pressure deficit (VPD; $R = -0.580$). These results suggest that unseasonal variation in LUE would be more affected by water conditions than leaf phenology or green leaf mass, and that the PRI has lower sensitivity for direct estimation of LUE compared to VPD in this evergreen tropical rainforest.

To improve the accuracy in estimating LUE, we examined the potential of combinational use of VIs and meteorological factors. Variable selection by stepwise multiple regression showed that the best variable combination for LUE estimation was the PRI and VPD ($R = 0.612$). The relative root mean square error (*r*RMSE) in the simple regression models using PRI, VPD and PRI × VPD, and the multiple regression model using PRI and VPD, was 22.5%, 19.4%, 19.0% and 18.7%, respectively. Based on these results, we concluded that (1) the estimation method solely based on the PRI as in the case of other temperate deciduous forests is not suitable in the tropical evergreen rainforest, and (2) the combinational use of the PRI and VPD offers one of the better models for estimating LUE in tropical evergreen rainforests.

1. Introduction

The light-use efficiency (LUE) of vegetation cover, generally expressed as the ratio of gross primary production (GPP) to absorbed photosynthetically active radiation (APAR), is one of the most essential parameters in production estimation models for terrestrial ecosystems (Heinsch et al., 2003; King, Turner, & Ritts, 2011; Monteith, 1972, 1977; Running, Thornton, Nemani, & Glassy, 2000). LUE is also often referred to as light conversion efficiency (ε) or radiation-use efficiency (RUE). The observed value of LUE in forest ecosystems has generally ranged from 0.01 to 0.04 mol mol^{-1} (Goerner, Reichstein, & Rambal,

Abbreviations: APAR, absorbed photosynthetically active radiation; CCI, canopy chlorophyll index; EVI, enhanced vegetation index; FWHM, full width of half maximum; GPP, gross primary production; LUE, light use efficiency; NDVI, normalized difference vegetation index; PAR, photosynthetically active radiation; PRI, photochemical reflectance index; SWC, volumetric soil water content; T_{air}, air temperature; VI, vegetation index; VPD, vapor pressure deficit; WI, water index.

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http://dx.doi.org/10.1016/j.rse.2014.04.021
0034-4257/

2009; Jenkins et al., 2007; Nakaji, Ide, Oguma, Saigusa, & Fujinuma, 2007; Nichol et al., 2000, 2002; Strachan, Pattey, & Boisvert, 2002). Historically, spatial variations in LUE have been estimated using an empirical value for each vegetation type or environmental factor function (e.g. Potter et al., 1993; Ruimy, Saugier, & Dedieu, 1994). For example, in the MODIS GPP algorithm, one of the most commonly employed model approaches for global GPP estimation, seasonal variation in LUE is estimated as the product of maximum LUE (LUE_{max}) and two attenuation scalars that evaluate the responses of photosynthesis to vapor pressure deficit (VPD) and air temperature (T_{air}; Heinsch et al., 2003). The scalars range from 0 to 1.0, and are calculated using simple linear ramp functions of daily minimum T_{air} and VPD. Although the relationships between the scalars and the input parameters (e.g. VPD and minimum T_{air}) have been broadly defined in lookup tables for each biome, this algorithm does not include the vegetational parameter related to the response of photosynthesis to the varying environmental condition in the field. Therefore, the development of other methods to estimate the *in situ* response of LUE to field conditions is emerging as an important approach for monitoring the productivity response of diversified forests on a global scale.

From this point of view, several studies have attempted the remote estimation of variation in LUE in the field, employing optical remote sensing techniques such as calculating spectral vegetation indices (VIs) using spectral reflectance measurements made from above the canopy (including space; Nichol et al., 2002; Drolet et al., 2005, 2008; Garbulsky, Peñuelas, Papale, & Filella, 2008; Garbulsky, Peñuelas, Gamon, Inoue, & Filella, 2011; Nakaji et al., 2008; Hall et al., 2008; Hilker et al., 2011). One of the most promising VIs used in estimating LUE is the photochemical reflectance index (PRI; Gamon, Peñuelas, & Field, 1992; Peñuelas, Filella, & Gamon, 1995), which is generally calculated from spectral reflectance at 531 nm (the absorption band of xanthophyll) and 570 nm. The PRI of green leaves shows diurnal variation due to light-dependent changes in the chemical composition of xanthophylls, which play a role in photoprotection (Gamon & Surfus, 1999; Nakaji, Oguma, & Fujinuma, 2006; Peñuelas, Gamon, Fredeen, Merino, & Field, 1994). In terms of the timescale of seasonal variation, PRI is affected by the balance of foliar pigments such as chlorophyll and carotenoids (Filella, Peñuelas, Llorens, & Estiarte, 2004; Filella et al., 2009; Nakaji et al., 2006; Peñuelas et al., 1994; Sims & Gamon, 2002). Since these variations are indirectly linked to the control and maintenance of photosynthetic efficiency, the PRI has been thought to be a useful indicator of LUE (e.g. Cheng et al., 2009; Drolet et al., 2005; Filella, Amaro, Araus, & Peñuelas, 1996; Nakaji et al., 2006; Nichol et al., 2000, 2002; Serrano & Peñuelas, 2005; Sims et al., 2006; Strachan et al., 2002). Furthermore, recently a number of studies have noted the utility of PRI for detecting changes in LUE in response to drought (Goerner et al., 2009; Hernández-Clemente, Navarro-Cerrillo, Suárez, Morales, & Zarco-Tejada, 2011; Moreno et al., 2012; Suárez, Zarco-Tejada, Berni, González-Dugo, & Fereres, 2009; Suárez et al., 2008; Zarco-Tejada, González-Dugo, & Berni, 2012). In addition, since studies on the utility of satellite-derived PRI have also been started by some researchers (Drolet et al., 2005, 2008; Garbulsky et al., 2008; Hilker et al., 2011; Moreno et al., 2012; Rahman, Cordova, Gamon, Schmid, & Sims, 2004), understanding the effectiveness and uncertainty of this index in several forest types will be important for the development of a satellite-based monitoring algorithm of LUE in near future.

Foliar chlorophyll concentration and green leaf mass are also related to variation in LUE in the field. In the case of crop field studies, large seasonal variations in LUE have been estimated based on remotely sensed chlorophyll concentrations (Houborg, Anderson, Daughtry, Kustas, & Rodell, 2011; Wu et al., 2009), while in the study of a temperate coniferous forest, the canopy chlorophyll index (CCI), calculated from the derivative spectral reflectance around the red-edge position (Sims et al., 2006), showed a significant positive relationship with LUE (Nakaji et al., 2008). Although few studies have examined the relationship between LUE and the greenness-related VIs such as the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI; e.g. Asrar, Myneni, & Kanemasu, 1989; Gamon et al., 1995; Liu & Huete, 1995; Huete et al., 2002), these VIs sometimes show significant correlations with LUE when the variation in LUE is governed by green leaf mass (Garbulsky et al., 2011; Mänd et al., 2010; Nakaji et al., 2007; Peñuelas, Garbulsky, & Filella, 2011; Sims et al., 2006).

Although several studies have been done on optical remote sensing of LUE in evergreen forests, these studies have been conducted mainly in temperate coniferous forests (Cheng et al., 2009; Hermández-Clemente et al., 2011; Hilker et al., 2010; Nakaji et al., 2008) and Mediterranean forests (Garbulsky et al., 2008; Goerner et al., 2009; Moreno et al., 2012; Serrano & Peñuelas, 2005; Suárez et al., 2008), and information concerning tropical forests is very limited. In particular, our knowledge of the PRI sensitivity in tropical forests is limited to only one study in Botswana (Grace et al., 2007). Therefore, understanding the utility of VIs for LUE estimation in evergreen tropical forests is critical to the future discussion of remote sensing of GPP on a global scale. In this study, we attempt to estimate the LUE of an evergreen tropical rainforest using VIs.

Our research forest is a lowland dipterocarp forest in Peninsular Malaysia. In this forest, there would typically be less seasonality in productivity than in other deciduous forests, as there is no clearly defined dry/rainy season cycle, and little seasonal variation in the canopy leaf biomass (as measured by the leaf area index, LAI). Furthermore, a previous study by Kosugi et al. (2008) reported that GPP in this tropical rainforest is positively related to water status factors such as soil water content (SWC). Therefore, we predicted that the sensitivity of chlorophyll- and green leaf mass-related VIs (i.e. CCI, NDVI and EVI) to LUE would be relatively low compared to the stress-related index, PRI. Furthermore, if these VIs alone were not adequate to evaluate the variation in LUE, we expected that the combinational use of VIs and meteorological factors such as T_{air}, VPD and SWC could improve the accuracy in estimating LUE. In this study, we also tested the potential of water index (WI; Peñuelas, Filella, Biel, Serrano, & Save, 1993; Peñuelas, Pinol, Ogaya, & Filella, 1997) as a supplemental variable because the water status may affect LUE. The WI reflects the variation in the reflectance of water absorption band at 970 nm, and it can be an indicator of the water condition of the vegetation surface (Claudio et al., 2006; Harris, Bryant, & Baird, 2006; Peñuelas et al., 1993, 1997). Although the WI cannot detect the variation in LUE directly, if LUE will be reduced by severe drought, additional use of WI may be useful for LUE estimation. In addition, in the test of combinational use of VIs and meteorological factors, we tested the potential of the PRI as substitute index evaluating attenuation scalars in a linear ramp function model.

Therefore, in this study, we first investigated the correlations between LUE and VIs and meteorological parameters, and then analysed the effect of the combinational use of VIs and meteorological parameters on the accuracy of LUE estimation in an evergreen tropical rainforest.

2. Materials and methods

2.1. Study site

We observed the CO_2 flux and canopy spectral reflectance of the lowland dipterocarp forest at the Forest Research Institute Malaysia's (FRIM) Pasoh Forest Reserve (2°58' N, 102°18' E) in Peninsular Malaysia. This research site is one of the monitoring sites in the AsiaFlux network (for more information about the monitoring sites visit AsiaFlux's website at http://www.asiaflux.net). The elevation and area of the site are 75–150 m a.s.l. and 2450 ha, respectively. All measurements of atmosphere, canopy phenology and canopy reflectance were taken using instruments mounted on a 53-m flux-monitoring tower. The volumetric soil water content (SWC) was measured using nine sensors in three points located <20 m away from the monitoring