The linear relationship between canopy structure and maximum light use efficiency across biomes.

Summary

Introduction

Light use efficiency (LUE) is the efficiency of the plants to convert absorbed radiation into fixed carbon (Monteith 1972). At leaf scale, LUE is defined as the initial slope (quantum yield) of the light response curve (Björkman 1981). At the canopy scale, LUE is defined as the ratio of a canopy photosynthesis metric such as canopy gross primary production (GPP) divided by absorbed photosynthetically active radiation (APAR) (Gitelson and Gamon 2015). Maximum LUE (ε_{Max}) is an important parameter that shows the capacity of photosynthesis. The ε_{Max} is a function of leaf physiology and potentially fixed value among different type of plants. For example, (Bolton and Hall 1991) showed that the theoretical maximum efficiency of conversion of light under ideal condition to carbon is 13%. However, at canopy scale and within and between biomes theoretical ε_{Max} needs to downregulated due biophysical and environmental constraints such as temperature and water stress (Gan et al. 2021). The regulated maximum LUE (LUE_{Max}) is then $\varepsilon_{Max} \times f(s)$, where $f(s)$ is usually various environmental stressors.

The variation of LUE_{Max} is of interest since it provide critical information of the state of an ecosystem regarding photosynthesis, also it is the basis of LUE based models of photosynthesis (Pei et al. 2022). The variation in LUE_{Max} has been attributed to a range of processes from ecological evolution (Field 1991) to water use efficiency, nitrogen, light quality, pigment distribution, vegetation type, atmospheric CO_2 (for a review refer to Gitelson and Gamon 2015; Gan et al. 2021). One aspect that has been highlighted as one of the main driver of changes in LUE is canopy structure. In an early study, (Medlyn 1998) showed that there the annual LUE is changing with leaf area index (LAI) but they did not present a clear relationship between the two variables. Recent advances in theoretical remote sensing provide means to stablish a link between canopy structure and LUE_{Max}. (Dechant et al. 2020) showed that up to 80% variation in GPP can be explained by

$$GPP = APAR \cdot fesc$$

APAR is absorbed photosynthetic radiation which can be calculated by:

$$APAR = PAR \cdot fPAR$$

Where PAR is the photosynthetic absorbed radiation and FPAR is the fraction of absorbed photosynthetic radiation. The variable fesc is the fraction of absorbed radiation that scape the canopy and it can be approximated by (Yelu et al):

$$fesc \approx \frac{NIRV}{fPAR}$$

Where NIRV can be acquired by multiplying normalized difference vegetation index ($NDVI = NIR - RED/NIR + RED$) by the reflectance values in the near infrared region of the spectrum (i.e. $NIRV = NDVI \cdot NIR$). A fesc is a function of multiple scattering inside the canopy which depends on canopy structure and leaf optical optical propertiese (i.e. reflectance and tranmittance).

On the other had from classical approach we have:

$$GPP = APAR \cdot LUE_{Max}$$

By comparing equation 1 and equation 2 we can observe that there should be a strong relationship between LUE_{Max} and fesc. Dechant et al for the first time showed a moderate positive relationship between daily LUE and fesc. However, there are a few challenges that makes the generalization of their approach limited. First, the daily LUE is not equal to LUE_{Max}. There are evidence that LUE is changing throughout the day and seasons while LUE_{Max} is more stable (Medlyn 1998). Thus the fesc-LUE relationship confound the impact of canopy structure with those related to other factors such as environmental factors. Moreover, this comparison is not consistent with equation 1 and equation 2, as that requires LUE_{Max} rather than LUE. Second, the stablished relationship is focused on three crop sites and by nature it is a temporal relationship. Although there is a change in canopy structure over time, but these changes are more prominent spatially and between different biomes. Overall, these factors limit the generalization of the stablished relationship to the larger spatial scales and within and between various biomes.

The main objective of this study is to overcome these challenges and study the relationship between fesc and LUE_{Max} over larger spatial scales. Considering equation 1 and 2, we hypothesize that there is a strong relationship between fesc and LUE_{Max}. This is because changes in canopy structure, hence fesc, is more dominant spatially over larger domain rather than temporally as in Dechant et al. To test this hypothesis, we pulled data from more than 270 eddy covriance sites along with remote sensing observations and investigated the relationship between the two variables between various biomes and between sites within a biome.

Materials and Methods

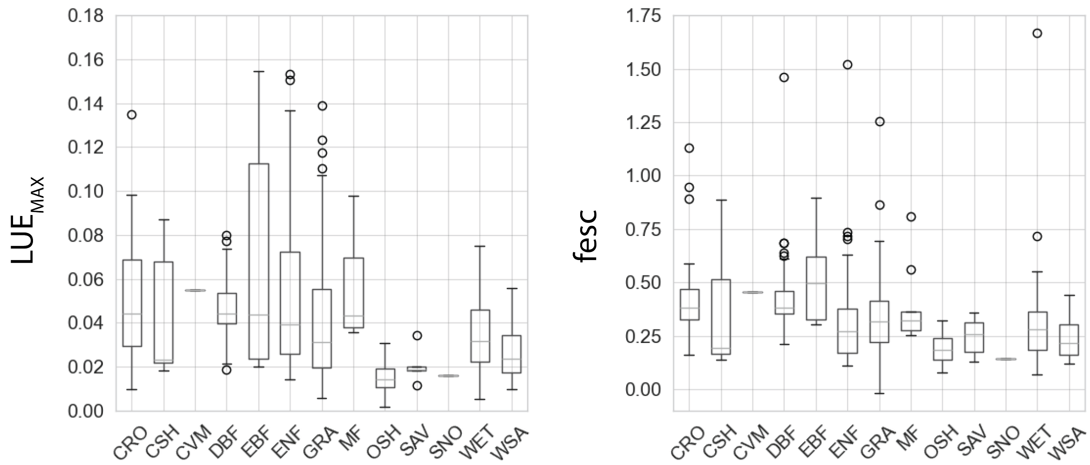
The eddy covariance (EC) data used in this study comes from two global EC netoworks, the FLUXNET2015 Dataset and AmeriFlux. Both datasets use the same pipeline to process data (Pastorello et al. 2020). If a site present in both datasets, we selected its data from AmeriFlux since it include most recent updates compared to its counterpart in FLUXNET. To calculate fesc we need reflectance and fPAR data. In this study we used MODIS products. The reflectance data is from daily MCD43A4 Version 6.1 Nadir Bidirectional Reflectance Distribution Function (BRDF)-Adjusted Reflectance product and the fPAR data is from MCD15A3H Version 6.1 Fraction of Photosynthetically Active Radiation product. Both products have a spatial resolution of 500 meter. The fPAR products has a 4 day resolution. To make them consistent with daily reflectance and EC data we used resample them to daily using linear interpolation.

From EC data we only used GPP and PAR data. We only used data where 20% or less have come from gap-filled data; NEE uncertainties are less than 3 g C $m^{-2}d^{-1}$, and 3) GPP partitioned with day- and night-time methods differ by less than 3 g C $m^{-2}d^{-1}$ (Joiner et al. 2018; Tramontana et al. 2016; Joiner and Yoshida 2020). The reflectance data we the red and NIR bands. We filtered data where the quality flag of each band indicate the good quality data where main BRDF algorithm has been used to process the data. Simillaryly for fPAR data we only used thos data were main radiative transfer algorithm has been used to drive fPAR, also there is no significant cloud presents in the scene.

After the pre-processing based on the flags we remove the outliers by calculating the stamdard deviation of each variable for each site across all the days, then only kept those data point that are within 2 standard deviation. Finally we were left with 276 sites which include 212552 days of data across 13 different biomes (Table XXX).

Biome	Abbreviation	Number of sites	Number of observations
Grasslands	GRA	48	36969
Mixed Forests	MF	9	7272
Evergreen Needleleaf Forests	ENF	67	48402
Open Shrublands	OSH	25	18744
Cropland/Natural Vegetation Mosaics	CVM	1	270
Permanent Wetlands	WET	29	17134
Woody Savannas	WSA	4	12756
Deciduous Broadleaf Forests	DBF	38	31851
Croplands	CRO	38	24540
Evergreen Broadleaf Forests	EBF	6	4337
Closed Shrublands	CSH	5	4285
Savannas	SAV	5	5771
Snow and Ice	SNO	1	221

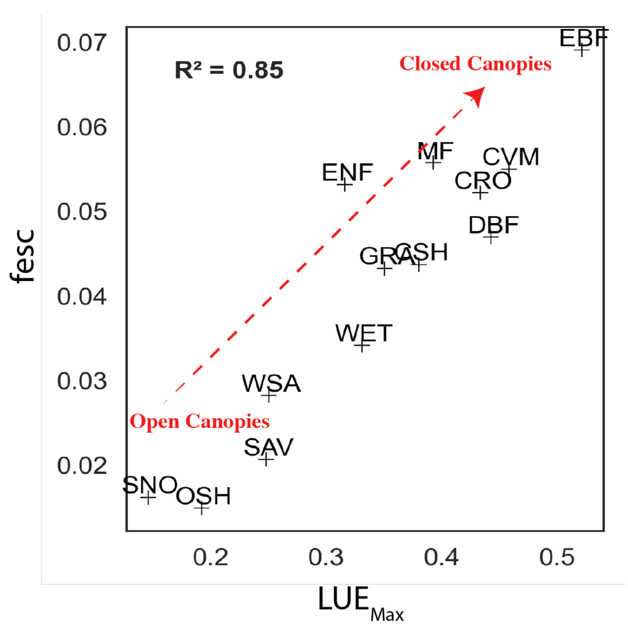
We calculated the daily LUE for each site as $LUE = \mathrm{GPP}/\mathrm{PAR} \cdot \mathrm{fPAR}$. Then we calculated the annual mean of the LUE as the LUE_{Max}. If a site had more than one year, then we take the median of max values for each year as the LUE_{Max}. We sued equation XXX to calculate the fesc. To show the relationship between fesc and LUE_{Max} between all biomes, we first grouped the LUE_{Max} and fesc data based on their biomes and we take the median and assigned it to each group. We also investigated the relationship between sites within each biome. For within biome analyses since the SNO and CVM has only one site, we drop them from within the biome analyses.



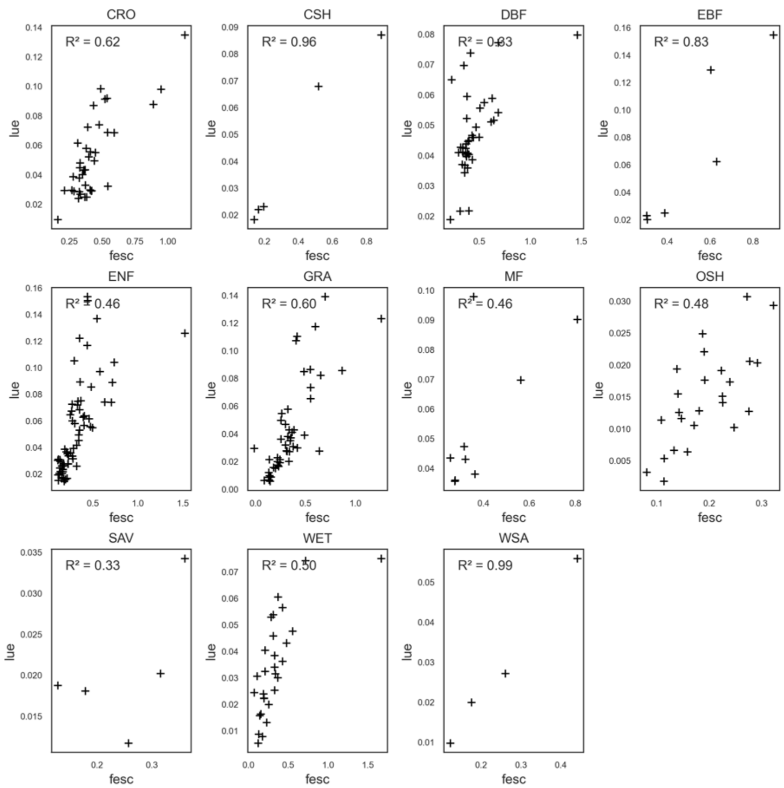
Results

Figure XXX shows the relationship between

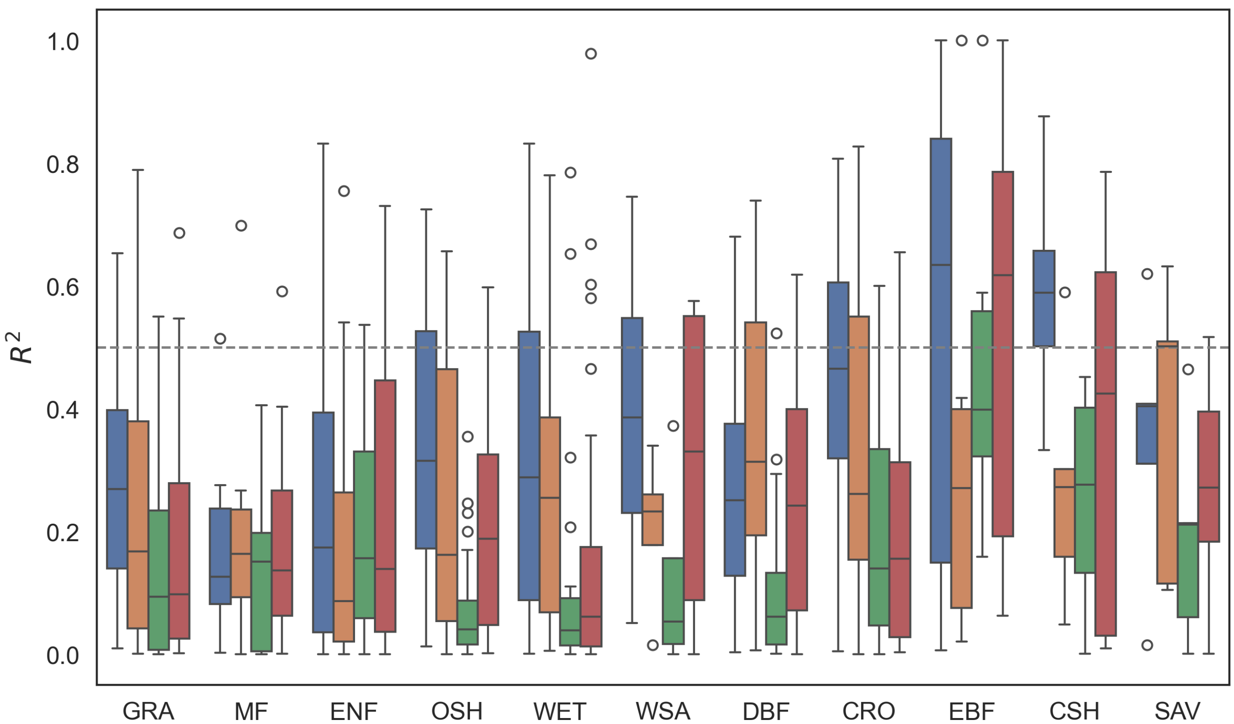
- There is a strong linear relationship between fesc and LUE when comparing between biomes. The R2 = 0.85
- There is a clear pattern where the open canopy have lower LUE and fesc are at the and as canopies get denser or closer both fesc and LUE max increases. For example ath the lower left we have open shrublands and savannas while at upper right we generally have forest and croplands.



Discussion



CRO
R² = 0.62
CSH
R² = 0.96
DBF
R² = 0.93
EBF
R² = 0.83
ENF
R² = 0.46
GRA
R² = 0.60
MF
R² = 0.46
OSH
R² = 0.48
SAV
R² = 0.33
WET
R² = 0.50
WSA
R² = 0.99
lue
fesc



Discussion

Physiological basis of the light use efficiency model with simulations showed that LAI does not explain the variability of light use efficiency. There are a few consideration, that canopy structure is more relvant at the large scales between PFTs