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Research Paper

Decadal trends in photosynthetic capacity and leaf area index inferred from satellite remote sensing for global vegetation types

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ABSTRACT

In the face of a mounting diversity of experimental, satellite and ground-based observations, it is becoming necessary to simulate *all* changes associated with vegetation (phenological, structural, physiological and biochemical) and to understand the links between them. In this respect, global land-surface models are an indispensible tool. These models require, above all, a temporally and spatially explicit parameterisation of light- and Rubisco-limited photosynthetic capacity in order to simulate photosynthesis accurately. The current study carries out a novel retrieval of these quantities by combining the standard satellite products of Leaf Area Index (LAI), from the Moderate Resolution Imaging Spectroradiometer (MODIS), with a hyperspectral index of total canopy chlorophyll concentration from the MEdium Resolution Imaging Spectrometer (MERIS). Monthly values of photosynthetic capacity are retrieved for the period 2002–2012 for global 0.5° landpoints and made available to the community. We examine the decadal trends in both photosynthetic capacity and LAI in order to ascertain biochemical and structural responses of vegetation to environmental change. The main conclusion is that these trends, if sustained, are of a sufficient magnitude to vie in importance with other environmental factors which affect vegetation productivity and carbon uptake (e.g. CO_2 fertilisation and climate). The decadal trends for Rubisco-limited photosynthetic capacity, which tend to be negative, depend more on plant functional type than latitude, suggesting that biochemical change, like physiological response (e.g. owing to CO_2 fertilisation), might best be monitored in terms of vegetation type rather than climate zone. We record an LAI trend which, globally, is flat (-0.2 ± 0.4% per decade) and, for the (mid-)northern latitudes, is much smaller (1.5–2.7% per decade) than that inferred by previous authors for Normalised Difference Vegetation Index (NDVI) during the 1980s (9–13%).

1. Introduction

Several landmark measurements reveal that the productivity of global vegetation is changing, although many details of the mechanisms remain elusive:

1. Remotely sensed NDVI (see Table 1 for acronyms used frequently in the text) reveals for the 1980s both an advancing spring (phenological change) and an increasing peak in productivity for northern latitudes (lat) > 40° (Myneni et al., 1997). The latter change is generally attributed to structural change (e.g. increased leaf area) but biochemical change (e.g. greater absorption of sunlight through leaf pigment change) cannot be excluded.
2. An increasing amplitude in the seasonal global atmospheric CO_2 concentration ([CO_2]; Keeling et al., 1996). This is generally interpreted as enhanced primary productivity in the high northern latitudes (Graven et al., 2013; Forkel et al., 2016), although an increase in carbon release during the dormant season as respiration cannot be totally excluded (Prentice et al., 2000; Graven et al., 2013).
3. An increase in both net leaf carbon uptake and ecosystem net primary productivity owing to increasing [CO_2] in Free-air CO_2 enrichment (FACE) experiments (Ainsworth and Long, 2005; IPCC, 2013). This "CO_2 fertilisation" appears, however, to vary according to Plant Function Type (PFT), with forests affected most (Norby et al., 2005; Luo et al., 2006). Furthermore, it is unclear whether the enhancement is sustained, given that nitrogen (N) is often limiting, even in temperate zones of high anthropogenic N-deposition (Townsend et al., 1996; Nadelhoffer et al., 1999; Cleveland et al., 2013; but see Lloyd, 1999). Paradoxically, there is also an expectation that active leaf-N (Rubisco and chlorophyll) may actually decline owing to acclimation to higher [CO_2] and diversion of plant-N to enhanced root growth (Prentice et al., 2000; Ainsworth and Long, 2005; Leakey et al., 2009).

In the face of these observations, it is becoming necessary to understand and simulate all changes associated with vegetation

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Table 1
An alphabetical list of acronyms, abbreviations and quantities used frequently in the main text. Units are given where appropriate.

	Definition
Chl	Leaf chlorophyll content (g m^{-2})
[CO_2]	Atmospheric CO_2 concentration (ppm)
FACE	Free-air CO_2 enrichment
J_{max}	Maximum electron transport rate (μmol m^{-2} s^{-1}) (light-limited photosynthetic capacity)
J^{25}_{max}	J_{max} at 25 °C (μmol m^{-2} s^{-1})
$J^{25,toc}_{cmax}$	J^{25}_{cmax} at canopy top (μmol m^{-2} s^{-1})
LAI	Leaf area index (m^2 m^{-2})
lat	Latitude (°)
MERIS	MEdium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MTCI	MERIS Terrestrial Chlorophyll Index
N	Nitrogen
NDVI	Normalised Difference Vegetation Index
PFT	Plant Functional Type
RMS	Root Mean Square
V_{cmax}	Maximum carboxylation rate (μmol m^{-2} s^{-1}) (Rubisco-limited photosynthetic capacity)
V^{25}_{cmax}	V_{cmax} at 25 °C (μmol m^{-2} s^{-1})
$V^{25,toc}_{cmax}$	V^{25}_{cmax} at canopy top (μmol m^{-2} s^{-1})

(phenological, structural, physiological and biochemical) as well as the interactions among them.

Global land-surface models, when supported by increasing field and satellite observations, are an invaluable tool in this respect and some of the latest models even couple the carbon and N cycles, so that changes in active leaf-N, for example, influence carbon assimilation (Zaehle et al., 2010; Smith et al., 2014). Above all, most land-surface and carbon models require a temporally and spatially explicit parameterisation of both light- and Rubisco-limited photosynthetic capacity in order to simulate photosynthesis accurately (Dang et al., 1998; Bonan et al., 2011). The advent of airborne and satellite hyperspectral instruments make this possible *via* remote sensing (Grace et al., 2007). However, many hyperspectral vegetation studies have hitherto focussed primarily on sun-induced fluoresence (which relates to chlorophyll) in agricultural areas (Zhang et al., 2014; Guanter et al., 2014) or the correlation of multiple optical and near-infrared wavelengths to leaf chemistry at *regional* level (Smith et al., 2002; Serbin et al., 2012; Ollinger et al., 2013). A more comprehensive study is called for, covering both natural and anthropogenic (e.g. agricultural) global PFTs, where N-limitations may differ.

The main purpose of the present study is to produce temporally resolved global maps of light- and Rubisco-limited photosynthetic capacity (J^{25}_{max} and V^{25}_{cmax}, respectively, for a standard leaf temperature of 25 °C), which are suitable for land-surface model parameterisation, as well as revealing spatial and temporal trends in active leaf-N. This is achieved by the novel step of combining LAI, inferred from MODIS broadband reflectance, with a hyperspectral index sensitive to ground chlorophyll concentration, derived from MERIS (operational period 2002–2012). Both datasets are satellite-based and quasi-global. The photosynthetic capacity (biochemical) trend will be compared with structural (LAI) change. Studies of remotely sensed LAI trend are fairly scant (Mao et al., 2013; Zhu et al., 2016), although the strongly related Normalised Difference Vegetation Index (NDVI) has been subject to trend analysis (Myneni et al., 1997; Zhou et al., 2001; Zhang et al., 2007; Los, 2013). Given its importance, few studies explicitly compare the contemporary period with the large increase in NDVI found by Myneni et al. (1997) for northern latitudes during the 1980s (but see Los, 2013).

Specific objectives of the current study are as follows:

1. To determine the magnitude and sign of biochemical (photosynthetic capacity) and structural (LAI) decadal trends and to compare them with the impact of CO_2 fertilisation on vegetation productivity.
2. To ascertain whether these trends correlate more strongly with latitude (as a proxy for climate) rather than with vegetation type.
3. To test whether the large increases in NDVI recorded during the 1980s (Myneni et al., 1997) are sustained and manifest themselves in LAI increases for the period 2002–2012.
4. To relate the spatial distribution of photosynthetic capacity to both vegetation type and latitude, comparing the retrieved global range with recent field-based compilations such as TRY (Kattge et al., 2009).
5. To make monthly 0.5° global maps of light- and Rubisco-limited photosynthetic capacity available to the community and thus considerably improve the land-surface model parameterisation for two of the most influential parameters determining carbon-exchange at the land-surface. The current parameterisation, based on general time-invariant values, is inadequate and often inconsistent (Rogers, 2014).

2. Material and methods

The methodology is introduced below in the following sequence:

1. conceptual background to the retrieval (Section 2.1);
2. input satellite datasets (MTCI from MERIS and LAI from MODIS) (Section 2.2);
3. protocol for retrieval (Section 2.3);
4. sensitivity analysis (Section 2.4);

2.1. Conceptual background

The retrieval combines the following 4 steps (see Alton, 2017 for detailed equations and a schematic overview):

1. Leaf measurements (discussed below) indicate a linear or saturating relationship between maximum electron transport for the light reaction (J^{25}_{max}) and leaf chlorophyll content (*Chl*);
2. The sum of *Chl* integrated over canopy LAI (i.e. chlorophyll concentration per unit ground) is detected with the hyperspectral index MTCI which has recently been calibrated against ground measurements of chlorophyll (Dash et al., 2010; Vuolo et al., 2012).
3. A fairly tight near-linear empirical relationship is observed between J^{25}_{max} and V^{25}_{cmax}, consistent with the optimisation of active leaf-N over a diverse range of C_3 plants (e.g. Wullschleger, 1993; Meir et al., 2002; Walker et al., 2014).
4. Thus, the chlorophyll concentration per unit ground, derived from remote sensing in step 2 above, can be related to Rubisco-limited photosynthetic capacity summed vertically over the canopy. Equivalently, using the observed exponential vertical decline in active leaf-N (Carswell et al., 2000; Lewis et al., 2000; Meir et al., 2002), we can retrieve V^{25}_{cmax} at the canopy top ($V^{25,toc}_{cmax}$) from known values of MTCI and canopy LAI.

The above 4 steps yield:

$$a_{\mathrm{mtci}}\mathbf{MTCI} - b_{\mathrm{mtci}} = \int_0^{\mathbf{LAI}} \frac{a_{\mathrm{wull}}}{a_{\mathrm{chl}}}\left[1 - \frac{b_{\mathrm{chl}}}{a_{\mathrm{wull}}} - \exp\left(\frac{-V^{25,\mathrm{toc}}_{\mathrm{cmax}}\exp(k_{\mathrm{rub}}L)}{b_{\mathrm{wull}}}\right)\right]\mathrm{dL} \quad (1)$$

where input satellite quantities have been highlighted in bold. Integration takes place over cumulative leaf area (L) from the canopy top to a depth into the canopy. Active leaf-N (chlorophyll and Rubisco) declines exponentially with L according to a vertical N-allocation parameter, k_{rub} (Hirose and Werger, 1987), which is assigned an

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