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Nitrogen Availability Dampens the Positive Impacts of CO₂ Fertilization on Terrestrial Ecosystem Carbon and Water Cycles

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Abstract

The magnitude and variability of the terrestrial CO₂ sink remain uncertain, partly due to limited global information on ecosystem nitrogen (N) and its cycle. Without N constraint in ecosystem models, the simulated benefits from CO₂ fertilization and CO₂-induced increases in water use efficiency (WUE) may be overestimated. In this study, satellite observations of a relative measure of chlorophyll content are used as a proxy for leaf photosynthetic N content globally for 2003–2011. Global gross primary productivity (GPP) and evapotranspiration are estimated under elevated CO₂ and N-constrained model scenarios. Results suggest that the rate of global GPP increase is overestimated by 85% during 2000–2015 without N limitation. This limitation is found to occur in many tropical and boreal forests, where a negative leaf N trend indicates a reduction in photosynthetic capacity, thereby suppressing the positive vegetation response to enhanced CO₂ fertilization. Based on our carbon-water coupled simulations, enhanced CO₂ concentration decreased stomatal conductance and hence increased WUE by 10% globally over the 1982 to 2015 time frame. Due to increased anthropogenic N application, GPP in croplands continues to grow and offset the weak negative trend in forests due to N limitation. Our results also show that the improved WUE is unlikely to ease regional droughts in croplands because of increases in evapotranspiration, which are associated with the enhanced GPP. Although the N limitation on GPP increase is large, its associated confidence interval is still wide, suggesting an urgent need for better understanding and quantification of N limitation from satellite observations.

1 Introduction

The global atmospheric CO₂ concentration and surface temperature are predicted to keep increasing, due to the rising demand of fissile fuels. With a third of CO₂ emissions absorbed by global terrestrial ecosystems, the buildup of atmospheric CO₂ is abated (Le Quere et al., 2015). Yet the magnitude and regional distribution of the terrestrial carbon (C) sink at elevated CO₂ levels remain uncertain, due to our limited knowledge on vegetation responses to increased CO₂ concentration and nutrient limitation (Bellassen & Luysaert, 2014; Grassi et al., 2017; Le Quere et al., 2009; Le Quere et al., 2015; Li et al., 2016; Schimel et al., 2015).

Light use efficiency (LUE) models do not agree with process terrestrial biosphere models, which are independent or subcomponent of Earth system models (ESMs), on the net magnitude of the CO₂ fertilization effect on the terrestrial C budget (Smith et al., 2016). Nutrient limitation, particularly plant available nitrogen (N), has been hypothesized to limit the projected C sink enhancing mechanisms under climate change and CO₂ fertilization. While there is less debate on the increased plant productivity under elevated CO₂ (Ainsworth & Long, 2005; Leakey et al., 2009; Norby et al., 2005, 2010; Nowak et al., 2004), many studies found that leaf N, and therefore leaf chlorophyll content, are reduced with increasing CO₂ concentration accompanying the increased sequestration of N in long-lived biomass (Ågren & Kattge, 2017; Campo, 2016; Cotrufo et al., 1998; Fisher et al., 2013; Pellegrini, 2016; Reich et al., 2006), especially for young stands (LeBauer & Treseder, 2008), and tropical secondary forests (Davidson et al., 2007, 2004). As a result, potential increases in grass (Obermeier et al., 2016; Reich et al., 2014) and forest (Norby et al., 2010) productivity due to CO₂ fertilization are hampered by N limitation (Franklin et al., 2014).

Contrary findings also exist at the regional scale. Recently, Girardin et al. (2016) found little growth stimulation in Canada's boreal forest under half century of warming and CO₂ fertilization using tree-ring analysis. From C isotope analysis, van der Sleen et al. (2015) suggest that there is no growth stimulation of tropical trees from 150 years of CO₂ fertilization, though water use efficiency (WUE) increased. Some studies suggested that future productivity and C storage are limited by nutrient availability (Cleveland et al., 2013; Smith et al., 2014; Wieder et al., 2015; Zaehle et al., 2015; Zhang et al., 2014). Other observational studies suggest that intact tropical forests may not be limited by N (Hedin et al., 2009; Santiago & Goldstein, 2016) but by phosphorus (Cleveland et al., 2011) because of increased N influx (Liang et al., 2016).

Of the global C cycle, terrestrial gross primary productivity (GPP) is the largest flux (Gitelson et al., 2006; Le Quere et al., 2015). Quantitative estimates of the spatial and temporal distributions of GPP on regional to global scales are critical to understand the climate-C cycle relationship (Xia et al., 2015). Proper representation of the N availability across the globe in ecosystem models is vital to understand the mechanisms of nutrition limitation to CO₂ fertilization (Piao et al., 2013). Plants optimize N allocations within roots, stems, and leaves to adapt to the N availability. While plants prioritize N allocation to structural components in the early growing stage, the allocation of N to photosynthetic components such as chlorophyll and Rubisco is optimized according to environmental conditions. The amount, activity, and kinetics of Rubisco mediates the maximum rate of carboxylation (V_{cmax}), and chlorophyll is responsible for harvesting light, while leaf N content controls the amount of Rubisco and chlorophyll. Therefore, leaf chlorophyll content is closely related to vegetation photosynthesis capacity (Alton, 2017; Croft et al., 2017; Harris & Dash, 2011; Kattge et al., 2009). The

MEdium Resolution Imaging Spectrometer (MERIS) terrestrial chlorophyll index (MTCI) has been shown to be sensitive to vegetation chlorophyll content due to the presence of red edge spectral bands (Alton, 2017; Curran et al., 2007; Dash et al., 2010; Dash & Curran, 2004, 2007; Harris & Dash, 2011; Jin et al., 2012; Zhang & Liu, 2014).

Rather than modeling the complicated N cycles, the objective of this study is to directly utilize the time series (2003–2011) of MERIS MTCI as a proxy of ecosystem photosynthetic N to quantify N-constrained global GPP and evapotranspiration (ET) trends under elevated atmospheric CO₂ conditions.

2 Materials and Methods

We obtained the global MERIS MTCI time series over 9 years (2003–2011) and derived the MTCI trend for each pixel (Curran et al., 2007; Dash et al., 2010; Dash & Curran, 2004, 2007; Harris & Dash, 2011; Jin et al., 2012; Zhang & Liu, 2014). The trend is then further extrapolated back to 2000, and forward to 2015. The trend of MERIS chlorophyll information was then used as a proxy of the trend of the maximum rate of carboxylation at 25°C ($V_{\text{cmax}, 25}$) in an ecosystem model named the Boreal Ecosystems Productivity Simulator (BEPS) (Chen et al., 2007, 1999, 2012; He et al., 2014, 2017; Ju et al., 2006; Liu et al., 1997). The MERIS MTCI is derived based on Level 2 data which have been atmospherically corrected (Dash et al., 2010). Nguy-Robertson et al. (2015) found that the chlorophyll content is linear to MTCI values ranging from 2 to 10 for fertilized Maize, suggesting that saturation of MTCI is not a concern. Experimental data show that chlorophyll content is found to be linearly related to $V_{\text{cmax}, 25}$ (Croft et al., 2017; Houborg et al., 2013). BEPS is forced by the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA 2) data (Rienecker et al., 2011) and satellite observed leaf area index (LAI) (Liu et al., 2012) to predict GPP and ET in 1982–2015.

BEPS inherits the Ball-Woodrow-Berry equation to model stomatal conductance (Ball et al., 1987; Frank et al., 2015; Franks & Beerling, 2009). In this study, the stomatal response to rising CO₂ concentration, which is important to explain the WUE change, is illustrated in the supporting information (SI) (Text S2 and Figure S7).

We design three scenarios to simulate the coupled C-water cycles and qualify the N-constrained global GPP trend at elevated CO₂ using BEPS, which is a two-leaf enzyme kinetic terrestrial biosphere model: (1) a BEPS run without CO₂ fertilization and N constraint, (2) a BEPS run with CO₂ fertilization but without N constraint, and (3) a BEPS run with both CO₂ fertilization and N constraint. Global GPP estimates from BEPS are also compared to results from another process-based model, the Breathing Earth System Simulator (BESS) (Jiang & Ryu, 2016), model tree ensemble from Max Planck Institute for Biogeochemistry (MPI-BGC) (Jung et al., 2011), and a light use efficiency model, Moderate Resolution Imaging Spectroradiometer (MODIS) (Mu et al., 2011). The Mann-Kendall test is used for trend analysis in this study.

To illustrate the usefulness of MTCI data for GPP simulation, we run BEPS for the same scenarios at the flux tower sites using remote sensed data in moderate resolutions, that is, LAI data in 500 m, and MTCI data in 300 m. The BEPS simulations are compared to eddy covariance data (FLUXNET2015 Dataset in Tier 1; <http://fluxnet.fluxdata.org/>).

More detailed descriptions of model, data, and design of experiment are listed in SI (Baldocchi, 1994; dePury & Farquhar, 1997; Feng et al., 2007; Friedl et al., 2002; He et al., 2012, 2016; Ju et al., 2010; Liu et al., 2012; Matsushita et al., 2004; Matsushita & Tamura, 2002; Medlyn et al., 1999; Monteith, 1965; Norman, 1982; Sellers et al., 1996; Sitch et al., 2008; Wang et al., 2004).

3 Results and Discussion

We describe the trends of MTCI, GPP and ET in the following sections, while their detailed summaries are provided in SI.

3.1 MTCI Trend

The largest annual mean MTCI values, as a proxy for leaf photosynthetic N content, appear in the tropical evergreen forests due to their longest growing seasons, followed by temperate forests and croplands (Figure 1a, for year 2003). The annual maximum MTCI values appear in cropland largely due to inputs from fertilizer application. The MTCI trends during 2003–2011 (Figure 1b) differ greatly among regions, with statistically significant increasing trends generally appearing in human managed ecosystems, that is, croplands, whereas neutral or decreasing trends are located in natural ecosystems, for example, tropical and boreal forests, and savannas (sensitivity analysis results are available in the supporting information (SI)). There are also increasing MTCI trends in far east of Russia close to newly developed farmland, consistent with increasing vegetation activity in the area (Gonsamo & Chen, 2016). The maximum positive MTCI trends appear in cereal and broadleaf croplands in Asia and South America. The MTCI trend map reveals enhanced fertilizer application and atmospheric N deposition over China (Liu et al., 2013; Lu et al., 2016) as well as the rest of the world (Reay et al., 2008). The MTCI trends in U.S. and Europe croplands are not as strong as that in Asia due to N mitigation (Zhang et al., 2015) as evidenced by independent satellite observations (Lu et al., 2016). Globally, 56% of the pixels show decreasing trends in MTCI (SI). The steepest decline in MTCI appears in broadleaf forests in South America. Considerable negative MTCI trends in tropical rain forests are related to recent deforestation, which cause N loss in the ecosystems (Deegan et al., 2011; Neill et al., 2006). Decreases in MTCI in tundra vegetation may be related to Arctic “browning” (Phoenix & Bjerke, 2016), where tundra turned into shrubland with longer N turnover times. The Mann-Kendall test shows that LAI, which is derived from an independent satellite sensor the Moderate Resolution Imaging Spectroradiometer (MODIS), has different trend patterns from MTCI during

the same period, suggesting that leaf chlorophyll and LAI have different physiological controls (Croft et al., 2014) (SI).

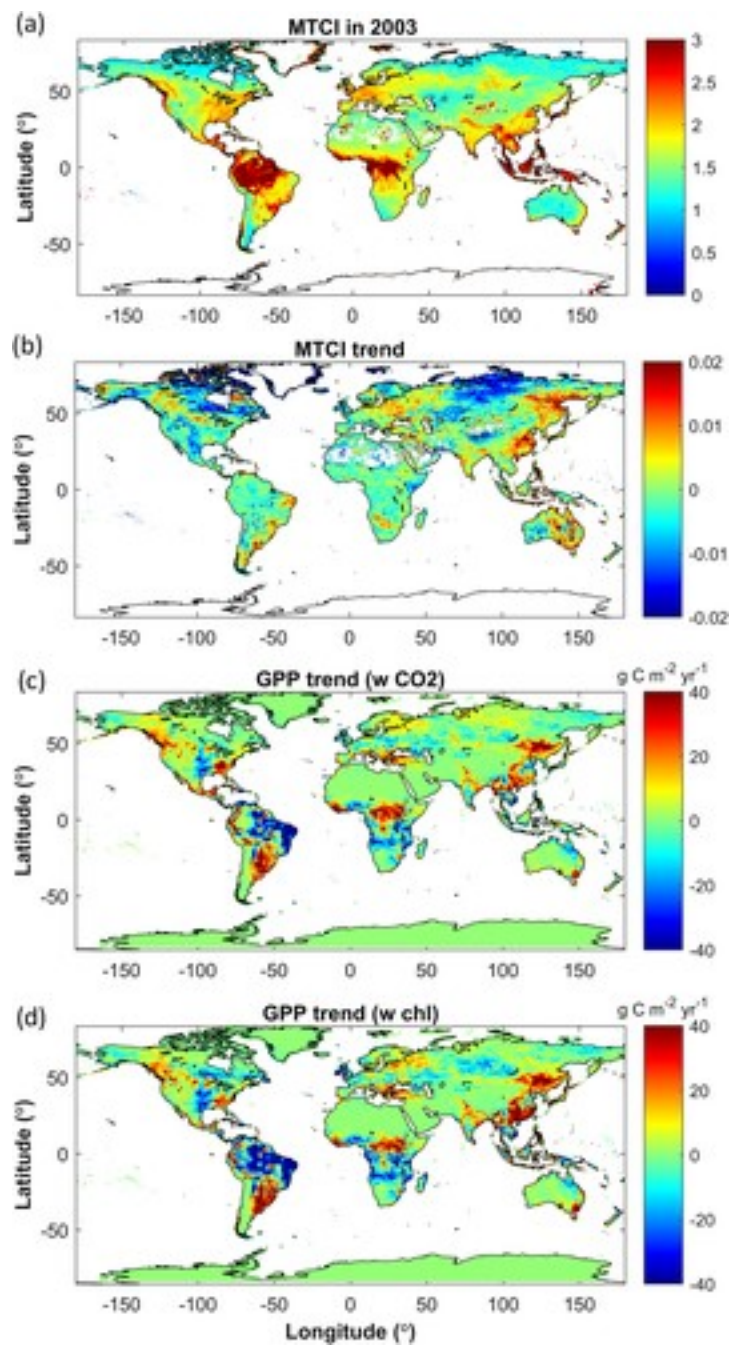


Figure 1

The trends of MTCI and global GPP by Mann-Kendall test. (a) The mean value of MTCI in 2003. (b) The relative MTCI trend from 2003 to 2011. Relative MTCI trend is the division of MTCI trend by MTCI mean. (c and d) The global GPP trends in 2000–2015 without and with nitrogen constraint proxied by MTCI are shown, respectively.

3.2 Impacts of CO₂ Fertilization and N Constraint on Global GPP Trend

At the site level, the consideration of N constraint in BEPS explains more interannual variance in simulated GPP by up to 4%, compared to simulations with only CO₂ fertilization (SI). This suggests the usefulness of MTCI in indicating N availability in ecosystems.

Without the consideration of N constraint, global simulations from BEPS suggest that there are both increasing and decreasing trends of GPP in the tropical forests during 2000–2015 (Figure 1c). BEPS simulations have captured the decrease of GPP in tropical forests due to the recent and the strongest El Niño–Southern Oscillation (ENSO) ever recorded. The large patches where GPP increases appear in croplands and forest areas related to regeneration in central Africa and regrowth from mountain pine beetle infestation in western North America. With N constraint (Figure 1d), there are intensified GPP increases in croplands except in Europe and U.S. that may be related to N pollution mitigation (Zhang et al., 2015), while extensive GPP decreasing trends are found in tropical and boreal forests.

With the consideration of CO₂ fertilization (Figure 2a), BEPS simulations suggest that global GPP increased from 116.2 Pg C yr⁻¹ in 1982 to 122.6 Pg C yr⁻¹ in 2015, with an increasing trend of 0.2 Pg C yr⁻¹ ($p = 6.8e-08$), or 5.5% in total, which is compatible to the NPP estimate (7.6%, 1982–2011) from an ensemble of Earth system models (ESMs) (Smith et al., 2016). The magnitude of the global GPP simulations from BEPS is similar to those of BESS (Jiang & Ryu, 2016) and MPI-BGC (Jung et al., 2011), while BEPS and BESS GPP estimates share common interannual variations in response to ENSO events as indicated by the multivariate ENSO index (MEI) (Wolter & Timlin, 2011). BEPS global GPP explains 25% ($p = 0.0025$) of interannual variance in residual C sink (Le Quere et al., 2015). Compared to a net primary production (NPP) derived from an artificial neural network data mining approach with an accuracy 0.72 (Li et al., 2017), the global GPP time series from BEPS can explain 45% ($p = 0.0001$) of interannual variance in this NPP product. Our result echoes the finding of Yue et al., (2015) which suggests that CO₂ fertilization is the dominant driver of the GPP trend from a 30 year simulation of global GPP.

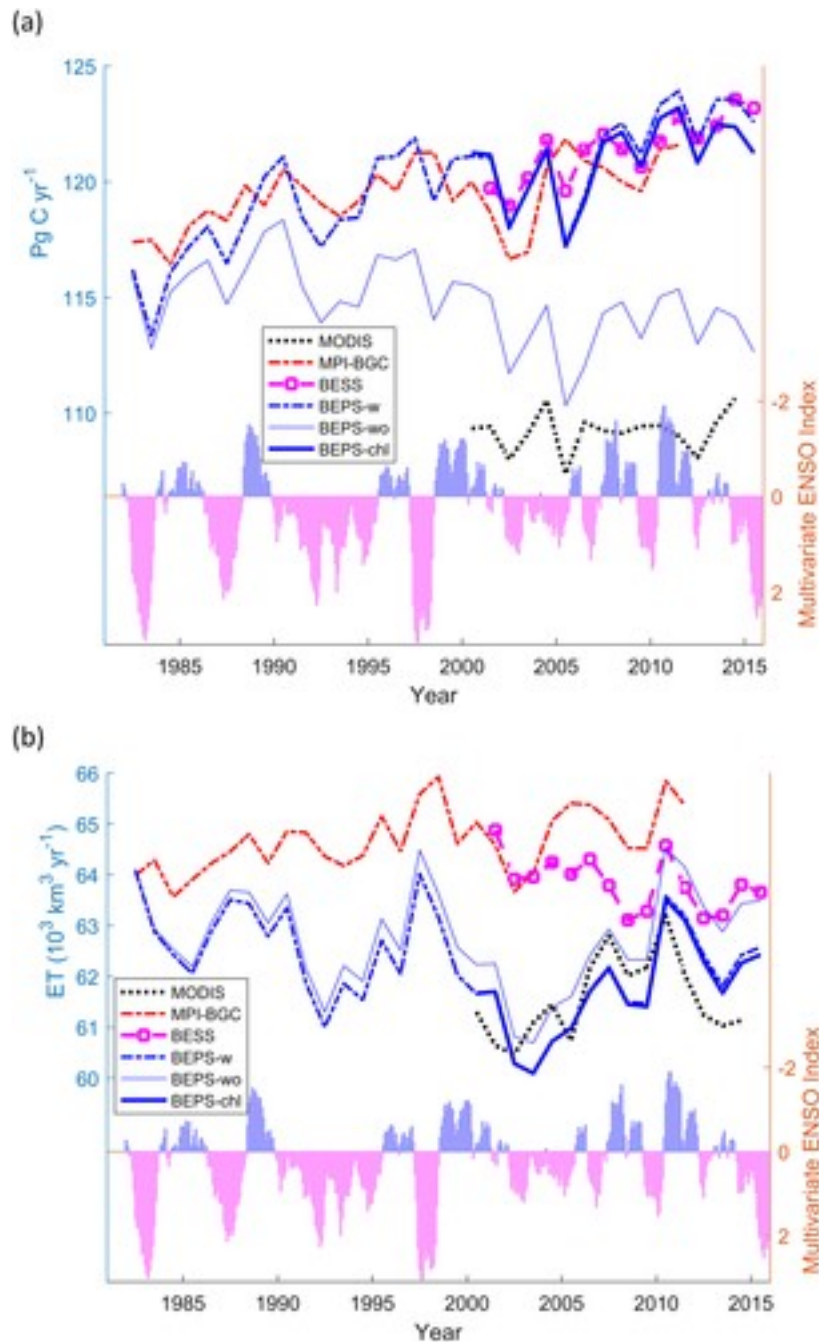


Figure 2

Time series of global (a) GPP and (b) ET estimates from different models and scenarios overlapped with multivariate ENSO index. BEPS-wo, BEPS-w, and BEPS-N indicate that the GPP and ET estimates are simulated without CO₂ fertilization, with CO₂ fertilization only, and with both CO₂ fertilization and N constraint, respectively. MODIS indicates estimation from the MODIS GPP and ET products. MPI-BGC indicates model tree ensemble-based estimate. BESS indicates estimation from the Breathing Earth System Simulator. In Figure 2a, the difference between BEPS-N and BEPS-w indicates the reduced GPP trend with N constraint. In Figure 2b, the difference between BEPS-w and BEPS-wo indicates ET decrease gained from CO₂-induced WUE increase.

Without CO₂ fertilization, BEPS shows a decrease in GPP by $-0.08 \text{ Pg C yr}^{-1}$ ($p = 0.0058$) or -3% over the 34 years; this value is lower

than the estimate of the ensemble ESMs (-1.7% in 1982–2011) since data during the last ENSO event (2014–2015) are included in BEPS. The MODIS GPP estimate (Mu et al., 2011), which does not include an explicit CO_2 fertilization effect, shows lower overall GPP and no significant trend ($0.019 \text{ Pg C yr}^{-1}$ in 2000–2014, $p = 0.43$), similar to the trend in BEPS simulation without considering CO_2 fertilization ($0.015 \text{ Pg C yr}^{-1}$ and $p = 0.96$ during the same period).

Considering both CO_2 fertilization and N limitation as represented by MTCI trends, the global GPP estimates by BEPS are 121.2 and $120.9 \pm 1.7 \text{ Pg C yr}^{-1}$ in 2015 and 2000–2015, respectively, and the global GPP trend during 2000–2015 is $0.13 \text{ Pg C yr}^{-1}$ with confidence interval (CI) in $[-0.02, 0.36]$ ($p = 0.079$), which is only 54% of the estimated trend ($0.24 \text{ Pg C yr}^{-1}$, $p = 0.0034$, CI = $[0.10, 0.48]$) with only CO_2 fertilization in BEPS for the same period. The global GPP estimates with N constraint decreased by 1.4 and 0.5 Pg C yr^{-1} in 2015 and in 2000–2015, respectively, comparing to BEPS simulations considering only CO_2 fertilization without N limitation. Our result is consistent with the finding of Reich and Hobbie (2013) from a long-term open-air $\text{CO}_2 + \text{N}$ experiments (2001–2010) that the limited ambient N availability will dampen the capacity of terrestrial ecosystems to sequester large amounts of C in the future.

Considering both CO_2 fertilization and N constraint, we find maximum GPP trends in deciduous broadleaf forests in Australia ($27.6 \text{ g C m}^{-2} \text{ yr}^{-1}$), Africa ($21.2 \text{ g C m}^{-2} \text{ yr}^{-1}$), and Asia ($16.7 \text{ g C m}^{-2} \text{ yr}^{-1}$), followed by broadleaf ($15.5 \text{ g C m}^{-2} \text{ yr}^{-1}$) and cereal ($13.1 \text{ g C m}^{-2} \text{ yr}^{-1}$) croplands in Asia. Minimum trends are found in Evergreen broadleaf forest ($-19.0 \text{ g C m}^{-2} \text{ yr}^{-1}$) in South America, and grasslands in Europe ($-8.9 \text{ g C m}^{-2} \text{ yr}^{-1}$) and South America ($-7.4 \text{ g C m}^{-2} \text{ yr}^{-1}$) (Table S2 in supporting information).

As suggested by Wieder et al. (2015), consideration of both N and phosphorus limitations may not change the global GPP trend significantly, comparing to only considering N limitation.

3.3 Impacts of CO_2 Fertilization and N Constraint on Global ET and WUE Trends

Global ET from BEPS is similar to that from MPI-BGC ($64 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$) (Figure 2b). However, their trends differ: MPI-BGC ET shows an increasing trend in 1982–2011 at the rate of $0.039 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$ ($p = 0.0015$), while BEPS shows decreasing trends in 1982–2015 at the rates of $-0.024 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$ ($p = 0.3918$, insignificant), $-0.054 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$ ($p = 0.0168$), and $-0.057 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$ ($p = 0.0125$) for the three scenarios: (1) without CO_2 fertilization, (2) with CO_2 fertilization only, and (3) with CO_2 fertilization and N constraints, respectively. BEPS ET estimates in the first few years may be positively biased due to uncertainty from model spinning up. Excluding the data in the first 3 years, BEPS shows an ET increase until 1997, followed by a decrease since then, while the ET trends, 0×10^3 , -0.001×10^3 , and $-0.035 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$, for scenarios 1, 2,

and 3 in 1985–2015 are insignificant with $p = 0.5747$, 0.1302 , and 0.0931 , respectively. The average global ET estimates in 1982–2015 from BEPS for the three scenarios are 62.8 ± 1.0 , 62.2 ± 1.0 , and $62.2 \pm 1.0 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$, respectively. These estimates fall in the lower boundary of the MPI-BGC model tree ensemble of $65 \pm 3.0 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$ in 1982–2008 (Jung et al., 2010). The impact of N constraint on the global ET is less important than on the global GPP. Both BEPS and MPI-BGC show responses to a major ENSO event in 1998 with ET decreasing until 2002 due to soil-moisture anomaly (also see supporting information) (Jung et al., 2010). All models except BESS reveal that global ET increases from a trough in 2002 to a peak in 2010.

There are debates on the global ET trend with much uncertainty from the forcing data sets (Badgley et al., 2015; Dong & Dai, 2017). Positive trends were reported by Zhang et al. (2016) and Mao et al. (2015), while Zeng et al. (2012) showed that the increase in global land ET mainly occurred between the 1980s and the 1990s, and the trend over the 2000s is nonsignificant. During 1992–2005, BEPS simulation with CO_2 fertilization only shows an insignificant global ET trend ($-0.1341 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$, or -0.2% , $p = 0.1253$) which is close to 0.1% trend estimated from measured discharge (Knauer et al., 2017). BEPS, with coupled C-water cycle in the leaf level rather than the canopy level, stands out with a nonsignificant trend, which may be associated with increase of WUE.

Recent studies suggest that the ratio of intercellular to ambient CO_2 concentration (C_i/C_a) remains constant at elevated atmospheric CO_2 , and as a result, CO_2 -induced stomatal closure increases the WUE (Frank et al., 2015; Franks et al., 2013; Ito & Inatomi, 2012; Keenan et al., 2013). These effects are captured in BEPS. For the scenario with only CO_2 fertilization, BEPS shows that C_a increased by 18%, and C_i in both sunlit and shaded leaves increased by 19%, suggesting a nearly constant C_i/C_a ratio during 1982–2015; stomatal conductance reduced by 10%, while the WUE increased by the same percentage during the same period. Without considering CO_2 fertilization, BEPS shows no trend of WUE, while the LUE-based MODIS shows increasing WUE trend in 2000–2014.

The CO_2 enrichment and WUE increase are widely expected to counteract crop yield losses due to increasing droughts in this century (Swann et al., 2016). Our results (Figure 3a) show worldwide ET decrease and CO_2 -induced increase in WUE, especially in tropical forests. However, the expected benefits of CO_2 fertilization in WUE could be weakened by intensified N availability (e.g., fertilizer use) at the regional level (Liu et al., 2013; Reay et al., 2008). Due to N application and deposition that increase leaf V_{cmax} and stomatal conductance and enhance photosynthesis and transpiration, there are substantial ET increases in the croplands that could offset ET decreases due to CO_2 fertilization (Figure 3b). For example, the ET trends in Asian cereal and broadleaf croplands are 3.5 and 3.8 mm yr^{-1} in 2000–2015, respectively, if CO_2 fertilization is not considered. Considering CO_2 fertilization only, the corresponding trends are reduced to

3.3 and 3.7 mm yr⁻¹ for the same period. However, the corresponding ET trends are increased to 3.8 and 4.0 mm yr⁻¹, respectively, if both CO₂ fertilization and N application and deposition are considered.

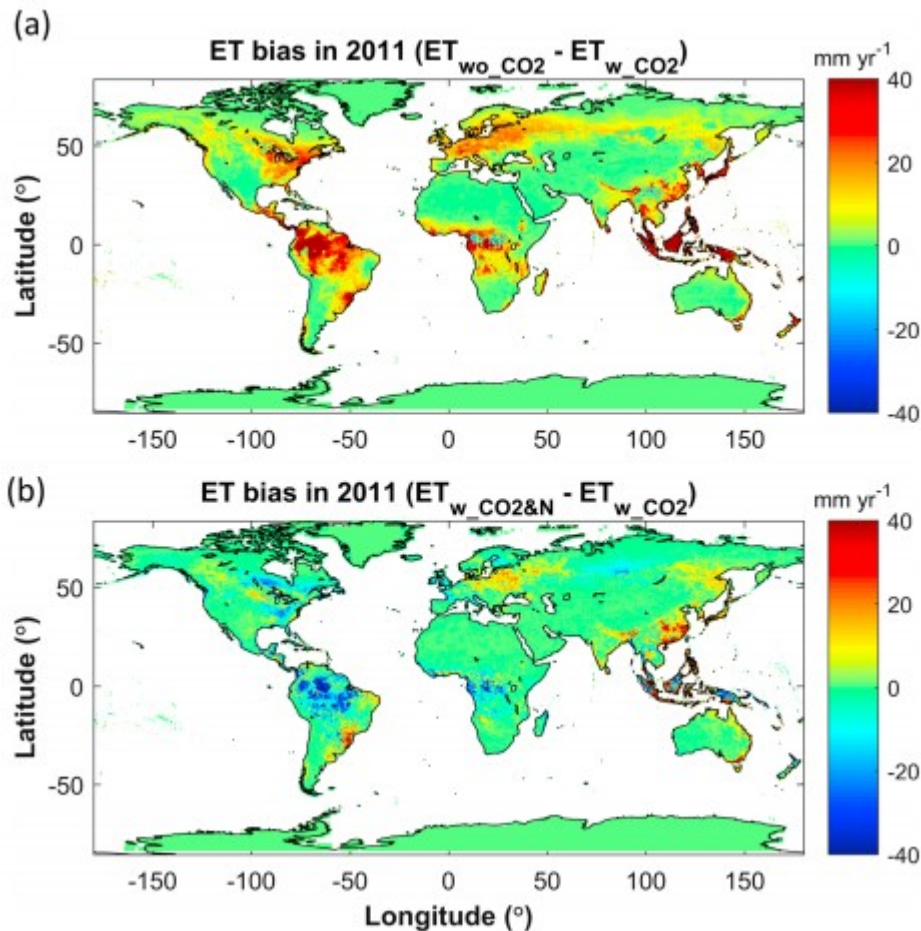


Figure 3

Global ET biases in 2011 due to missing CO₂ fertilization or N constraint. ET_{wo_CO2}, ET_{w_CO2}, and ET_{w_CO2&N} indicate ET estimations simulated by BEPS without CO₂ fertilization, with CO₂ fertilization only, and with both CO₂ fertilization and N constraint, respectively. (a) The ET bias due to CO₂ fertilization. (b) The ET bias due to N availability. ET decrease gained from CO₂-induced WUE increase can potentially be offset by ET increase accompanied by GPP increase due to N deposition at the regional level.

4 Discussions

In this study, we have compared three scenarios to separate the effects of CO₂ fertilization and N limitation in global ecosystems. The uncertainties from LAI product, the MERRA 2 meteorological forcing data, and other missing drives that may cause effects in capturing the global GPP and ET trends are data source specific, difficult to quantify, and cannot be ruled out. However, all these three scenarios shared the same input data and the only differences among them are the CO₂ concentrations and V_{cmax} trends; therefore, this enables us to isolate only the effects of CO₂ and N although other factors exist.

Our study highlighted the importance of N in global GPP and ET simulations. Due to the limited length of MERIS mission, only a time series of MTCI in 9 years is available for trend analysis; therefore, the trend of MTCI is not very strong in extensive area. Fortunately, with the launch of Sentinel-3A in 2016, the availability of MTCI data is able to continue in the same bands and spatial resolution for seven more years and more robust MTCI trend analysis is possible in future.

The MTCI trend is used as a proxy of $V_{\text{cmax}, 25}$ trend at the top of canopy. Other V_{cmax} variations, such as its gradient in canopy profile and temperature response, are still explained by BEPS. Although use of intraannual variation of MTCI can further improve BEPS performance, we still assume that $V_{\text{cmax}, 25}$ is a constant during a year in this study, in order to keep the three scenarios comparable.

The advantage of our approach is that we use spatially explicit variation of MTCI trend in global scale to constrain N rather than a modeling approach which has to involve many assumptions. The use of MTCI also has limitations because we have assumed that the trend of MTCI is linear and the $V_{\text{cmax}, 25}$, chlorophyll content and MTCI share the same trend. Although the correlations between $V_{\text{cmax}, 25}$ and chlorophyll content (Croft et al., 2017; Houborg et al., 2013) and between chlorophyll content and MTCI (Nguy-Robertson et al., 2015; Peng et al., 2017) are strong, more studies that directly use of MTCI for GPP modeling, such as Alton (2017), Boyd et al. (2012), Dong et al. (2015), Harris & Dash (2011), and Loozen et al. (2017), will further strengthen the conclusion of this study.

5 Conclusions

Estimates of the global terrestrial GPP trend induced considerable debates arising from lack of N constraint in ESMs (Norby et al., 2010; Obermeier et al., 2016; Reich et al., 2014; Santiago & Goldstein, 2016; Schimel et al., 2015; Smith et al., 2016, 2014; Thornton et al., 2007; Wieder et al., 2015; Zaehle et al., 2015; Zhang et al., 2014). Here we make use of a global time series of satellite-observed MTCI vegetation index data to provide a proxy for leaf photosynthetic N content in order to constrain the vegetation photosynthesis capacity in an ecosystem model. The results indicate that there are extensive decreases in photosynthetic capacity in tropical forests and part of boreal forests, and this negative effect on the global vegetation productivity is mostly offset by enhanced N deposition in croplands. With N constraint, the simulated global terrestrial GPP decreased by 1.4 Pg C yr^{-1} in 2015, dampening our expectation for the enhanced CO_2 fertilization. Our result may provide new explanation for the discrepancies between Smith et al. (2016) and De Kauwe et al. (2016) regarding the large divergence of LUE-based and ESMs estimates of global terrestrial CO_2 fertilization. Therefore, the consideration of both LUE increase and reduced CO_2 fertilization under N limitation is necessary for accurate projections of future C-climate feedbacks for different Representative Concentration Pathways.

Allowing N application and deposition to counteract the CO₂-induced WUE increase could also limit the optimism for reduced water management requirements for crops. We found that the 10% increase of WUE in 1982–2015 from CO₂ fertilization can be offset by ET increase accompanied by enhanced growth due to N fertilizer application in China's croplands. Crop production needs to increase by about 60%–100% from 2007 to 2050 to meet global food demand (Zhang et al., 2015). As the demand on crop yields continues to grow (Sanchez, 2010), especially in developing countries, there will be enhanced N application in agriculture accompanied by expansion of irrigated areas in the future (Fishman et al., 2015), resulting in large modifications to terrestrial nutrient, carbon, and water cycles that have not been considered in most ESMs (Swann et al., 2016).

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