

## Responses to the Referee's Comments

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We would like to thank the editor's decision regarding the revision of our manuscript. We are greatly thankful for the insightful and constructive comments from the anonymous reviewer. We have carefully studied them and revised the manuscript accordingly. This document contains our specific responses to the comments.

### Responses to Anonymous Referee #1's Comments:

*1. Throughout the paper the authors use the term "feedback" to refer to the "effect" of NPP on ET. I don't think "feedback" is the proper term here. "Feedback" means response. But I don't think the authors meant to say that ET first acts on NPP, and then NPP reacts on ET. Here "feedback" should be from NPP to climate. As the authors correctly stated in the paper, ET is the process that connects vegetation and climate, i.e., NPP can have feedback to climate through ET, but not have feedback to ET itself.*

**Response:** Thanks for the reviewer's comment. We corrected the title as "Dynamic changes in terrestrial net primary production and their effects on evapotranspiration", also corrected it in the main text.

*2. The authors found association/correlation between NPP and ET. However, correlation does not necessarily mean causal relationship. Among the three things: NPP, ET, and climate (temperature and precipitation), which one affects which one is a complex issue. The authors want to more clearly sort out the relationships among the three and be cautious on making strong statement that NPP is the cause for the change of ET.*

**Response:** Table 1 and its description in the text are the correlations between NPP and four climatic variables (temperature, precipitation, net radiation and PDSI) for over both hemispheres. We have not made the quantitative association/correlation between NPP and ET. We just wanted to show that: Land actual evapotranspiration (ET) changes are positively with net primary production changes, especially in the Northern Hemisphere. Under the context of past warmest 15 years, the slightly increased inter-annual series of NPP and climate change promote decadal rises of global land ET. According to the reviewer's comment, we corrected several sentences

that seem strong statement that NPP is the cause for the change of ET. e.g. Abstract and 3.1 Spatiotemporal variation in global terrestrial NPP and its effects on ET.

**Abstract.** The Earth has experienced a dramatic increase in global climate warming since 2000, which has significantly influenced the global water cycle and vegetation activities. Despite these radical changes, there is little observational evidence to demonstrate the effects of vegetation variations on climate in different global geographical units. A few studies focused on feedback relating to the inter-annual variability of vegetation on the physical processes of atmosphere-land surfaces, especially with regards to evapotranspiration. Overall, the global inter-annual series of net primary production (NPP) slightly increased in 2000-2014 at a rate of 0.06 PgC/yr<sup>2</sup>. More than 64% of vegetated land in the Northern Hemisphere (NH) showed increased NPP (at a rate of 0.13 PgC/yr<sup>2</sup>), while 60.3% of vegetated land in the Southern Hemisphere (SH) showed a decreasing trend (at a rate of -0.18 PgC/yr<sup>2</sup>). Temperature was the dominant control factor for vegetation growth in high latitudes in the NH, net radiation and precipitation were the main factors affecting NPP in the mid latitudes, and warming-associated large-scale drying trends led to decreases in NPP in the SH.

Vegetation productivity influences albedo and emissivity, both of which regulate evapotranspiration (ET). Changes in actual ET correlate positively with changes in NPP, especially in the NH, where increased vegetation productivity and climate change have promoted sharp rises in terrestrial ET (0.61 mm/yr<sup>2</sup>). At the same time, anomalous dry conditions have caused a reduction in vegetation productivity and a near cessation of terrestrial ET growth in the SH (0.41 mm/yr<sup>2</sup>). Although water vapor via vegetation transpiration can lead to increased regional atmospheric humidity over a short time span, it also preserves less water in the soil. This, in turn, accelerates reductions in soil moisture caused by warming and triggers negative feedback. Drought indices, along with precipitation-minus-evaporation calculations, point to an increased risk of drought in the 21st century.

### **3.1 Spatiotemporal variations in global terrestrial NPP and their effects on ET**

The spatial patterns of global NPP from 2000 to 2014 showed a steadily decreasing trend from the equator to the Arctic and Antarctic (Fig. 1c). Overall, the inter-annual series of NPP increased moderately at a rate of 0.06 PgC/yr<sup>2</sup> over the past 15 years, and also shows different changes in the Northern and Southern Hemispheres. While

NPP in most parts of the NH increased (Fig. 1a), it decreased in most parts of the SH (Fig. 1b). Specifically, in the NH, 64% of vegetated land area experienced increased NPP, including large areas of North America, Western Europe, India, and eastern China. Regions with decreased NPP include Eastern Europe and higher latitudes of central and west Asia. In the SH, decreased NPP accounted for about 60.3% of vegetated land area, mainly concentrated in South America, South Africa, and western Australia. Furthermore, in the equatorial regions, Amazon rainforests had significantly decreased NPP, whereas African rainforests experienced an increasing trend (Fig. 1c). Because tropical rainforest NPP accounts for a large proportion of global NPP, decreases in SH NPP partially counteracted increases in NH NPP.

When we combined global LUCC characteristics, the results showed that shrubland has the greatest potential increasing trend of NPP ( $16.5 \text{ gC/m}^2/\text{yr}$ ) compared to other biomes, followed by grassland ( $12.5 \text{ gC/m}^2/\text{yr}$ ). This may be related to the expansion of woody vegetation over the past 15 years. In the Arctic tundra (Hughes et al., 2006) and lower latitudes in arid environments (Chen et al., 2014), experimental studies provided clear evidence that climate warming is sufficient to account for the expansion of shrubs and graminoids.

Changes in vegetation albedo and emissivity exert feedback on climate, which is especially obvious in ET (Field et al., 2007). The viability of vegetation cover can substantially modulate available surface energy and partition that energy into sensible and latent heat fluxes (Matsui et al., 2005). Vegetation changes can affect water and energy cycles in the land-atmosphere circulation by changing the physical characteristics of the land surface. For instance, the albedo of vegetation is less than that of bare soil, enabling it to absorb more energy and thus increase ET. Moreover, canopy height can change land surface roughness and affect the energy and momentum between land and air transport, and leaves promote ET through direct evaporation either from precipitation or transpiration interception from water uptake by roots.

Increased vegetation productivity and climate change may promote multi-decadal rises of global land ET (Zhang et al., 2015). Vegetation generally promotes land-atmosphere water exchange via transpiration through a biological process, changing soil moisture conditions and affecting the land-atmosphere feedback. The average mean of estimated global annual ET is  $518.6 \text{ mm/yr}$ , with an inter-annual trend of  $0.46 \text{ mm/yr}^2$ . Figures 1a and 1b show that the spatiotemporal changes of global ET are

consistent with NPP variations, especially in the NH. Furthermore, where their association is less than that in the NH, NPP and ET in the SH have much higher variability. The spatial inconsistency in the SH mainly occurred near the equator, e.g., southern African rainforests (Figs. 1b & 1d). These regions have high values of average annual precipitation and stronger variability of precipitation than elsewhere, causing greater changes to ET and its components (land-surface evaporation, canopy evaporation, and transpiration). In places where the inter-annual variability of NPP is small, the ET component of land-surface evaporation increases. In contrast, in areas with large inter-annual variability of NPP, such as shrubland and grass-dominant regions, the ET components of land-surface evaporation decline and transpiration increases.

*3. Section 3.2: The first paragraph has a logic problem: If your goal is to understand the response of climate to NPP, why do you want to study the climate controlling factors on vegetation? Shouldn't it be reversed?*

**Response:** Yes, this sentence is indeed reversed. “To understand why NPP variations in the Northern and Southern Hemispheres respond differently to different climates, we first estimated the spatial trends of climatic control factors and then analyzed the complex multiple climatic constraints to plant growth. ”

*4. One of the conclusions of the paper is that if the effect of NPP on ET continues, regional droughts may get exacerbated. NPP and ET have a positive correlation, and authors found that the general trend globally is that NPP is increasing. Does this mean that more NPP globally will lead to more droughts? This sounds counterintuitive.*

**Response:** To more clearly clarify the conclusion, we added the following relevant statements:

### **3.3 Continued effects of NPP on evapotranspiration likely to exacerbate regional droughts**

With respect to the impact of drought on the world's ecosystems, studies have been limited regarding the contribution of vegetation and terrestrial water cycle components to drought variations (Falloon et al., 2012; Teuling et al., 2013). However, the present lack of high-quality and long-term records of actual ET limits the forecasting of drought under climate change circumstances.

Drought indices are pointing to an increased risk of drought in the present century.

We used potential evapotranspiration (PET) as a surrogate measure of atmospheric moisture demand. PET is defined as the maximum quantity of water capable of being evaporated from soil and transpired from vegetation, whereas ET is the actual evaporation from water and soil, as well as transpiration from vegetation. Penman (1948) stated that ET had a proportional relationship with PET, and Bouchet (1963) hypothesized that a complementary feedback mechanism exists between ET and PET in water-limited regions. Overall, our investigation indicate that there is a proportional relationship between ET and PET in humid regions and a complementary one in arid regions (Fig. 1d and Fig. 4a). In PET, the combined impacts of temperature, solar radiation, vapor pressure and wind speed (Zhang et al., 2015) interact with NPP (Fig. 4b). Over the past 15 years, global PET showed an increasing trend of  $1.72 \text{ mm/yr}^2$ , while global P increased at a rate of  $0.84 \text{ mm/yr}^2$ . However, precipitation increases cannot offset evaporative demand, indicating a potential moisture deficit for water supplies constrained by ET. In other words, P is mostly being lost to ET rather than being allocated to other components of the energy and water cycles (Zhang et al., 2015).

Various factors, including vegetation, affect the intensity and spatial variation of drought. Vegetation generally promotes land-atmosphere water exchange via transpiration, changing soil moisture conditions and affecting the land-atmosphere feedback. Water vapor via transpiration can lead to increased regional atmospheric humidity over the short term, but preserve less water in the soil. This, in turn, accelerates reductions in soil moisture caused by warming and provides a negative feedback. Vegetation growth causes increased soil moisture evaporation, thus reducing the amount of soil water storage. Once vegetation suffers persistent drought, the vegetation biomass will rapidly decline and further intensify the drought. Thus, decreasing soil moisture tends to decrease net terrestrial radiation at the surface through increasing land-surface temperatures. If low levels of soil moisture persist for long enough, reductions in vegetation cover and vigor can occur. As land-surface temperatures rise, increases in precipitation are insufficient to offset increases in evaporative demand, indicating a potential moisture deficit for water supplies constrained by ET. This leads to soil water loss and reduced vegetation growth, along with higher risk of drought (Meng et al., 2014; Zhang et al., 2015). Soil moisture is an important sensor for measuring superficial wetness and dryness levels, and generally reflects the dryness and wetness of climate. Figure 5 illustrates the world-wide

decrease in soil moisture of four layers (0-10, 10-40, 40-100, and 100-200 cm). With precipitation being the most direct factor affecting soil moisture, temperature and solar radiation may cause soil moisture loss through ET. Available soil moisture is defined as the amount of water a plant can access in its root zone. Thus, spatial and temporal variations in soil moisture are closely related to vegetation growth (Davis and Pelsor, 2001; Yang et al., 2010).

*The added References:*

Falloon, P.D., Dankers, R., Betts, R.A., Jones, C.D., Booth, B.B.B. and Lambert, F.H.: Role of vegetation change in future climate under the A1B scenario and a climate stabilisation scenario, using the HadCM3C Earth system model. *Biogeosciences*, 9, 4739-4756, doi:10.5194/bg-9-4739-2012, 2012.

Meng, X.H., Evans, J.P. and McCabe, M.F.: The impact of observed vegetation changes on land-atmosphere feedbacks during drought. *J. Hydrometeorol*, 15, 759-776, doi:10.1175/JHM-D-13-0130.1, 2014.

Teuling, A.J., van Loon, A.F., Seneviratne, S.I., Lehner, I., Aubinet, M., Heinesch, B., Bernhofer, C., Grünwald, T., Prasse, H. and Spank, U.: Evapotranspiration amplifies European summer drought, *Geophys. Res. Lett.*, 40, 2071-2075, doi: 10.1002/grl.50495, 2013.

Zhang, K., Kimball, J.S., Nemani, R.R., Running, S.W., Hong, Y., Gourley, J.J. and Yu, Z.B.: Vegetation greening and climate change promote multidecadal rises of global land evapotranspiration, *Sci. Rep*, 5, 15956, doi: 10.1038/srep15956, 2015.

*5. Did the authors calculate NPP and ET by themselves or simply use the MODIS products. This should be more clearly described in the paper. If MODIS products were used, then no algorithm details are needed; simply refer to relevant MODIS references. If the authors calculated those values by themselves, then more technical details are needed, including image selection, processing, and calculation processes; and in this case, the authors also need to properly cite the references for those algorithms and processes.*

**Response:** We used the MODIS products and clarified them in the “2.1 Data”, meanwhile deleted the algorithm details from “2.2 Methods”.

## **2.1 Data**

The monthly grid data of the temperature and precipitation series from 2000-2014, with a spatial resolution of 0.5 degrees, were collected from the Climatic Research Unit (<http://www.cru.uea.ac.uk/data/>). The radiation and soil moisture data series was issued by the Global Land Data Assimilation System (GLDAS-1), with a spatial resolution of 0.25 degrees (<http://gdata1.sci.gsfc.nasa.gov/daac-bin/>

[G3/gui.cgi?instance\\_id=GLDAS025\\_M](http://G3/gui.cgi?instance_id=GLDAS025_M)). The depths of the four soil layers are: 0-10 cm, 10-40 cm, 40-100 cm, and 100-200 cm. The quality of the GLDAS data set was assessed against available observations from multiple sources (Zhang et al., 2008; Chen et al., 2013).

The monthly data of the Palmer Drought Severity Index (PDSI), with a spatial resolution of 2.5 degrees, was available at <http://www.cgd.ucar.edu/cas/catalog/limind/pdsi.html>. As an indicator of land-surface moisture conditions, PDSI has been widely used for the routine monitoring and assessment of global and regional drought conditions. The global dry areas were defined as  $PDSI < -3.0$ , while the wet areas were defined as  $PDSI > +3.0$  (Dai et al., 2004).

We used the Global Land Cover Characterization data from the International Geosphere-Biosphere Program (IGBP) in 2000 (<http://edc2.usgs.gov/glcc/glcc.php>), along with MODIS in 2000 and 2013 (<http://modis.gsfc.nasa.gov/data/dataproduct/mod12.php>). From these data, a routinely integrated classification of land use/cover change (LUCC) characteristics was obtained based on the feature fusion processes.

The global 1-km MODIS NPP datasets (2000-2014) are from MOD17. NPP estimations are typically model-based and biogeochemical, and are generated from a larger set of simulated C fluxes between the atmosphere and terrestrial ecosystems (Ito et al., 2011). A better agreement of MODIS and terrestrial NPP estimates allows the use of MODIS in large-scale estimates (Neumann et al., 2015).

The MODIS evapotranspiration datasets (2000-2014) from MOD16 are estimated using Mu and colleagues' (2011) improved ET algorithm over Mu et al.'s (2007) previous paper. Based on the energy-balance theory and the Penman-Monteith equation, the required MODIS data inputs for the ET algorithms include daily meteorology (temperature, actual vapor pressure, and incoming solar radiation) remotely-sensed land cover, FPAR/LAI, and albedo (Friedl et al., 2010; Myneni et al., 2002). We unified the spatiotemporal resolution of these data from different sources, based on re-sampling (nearest neighbor interpolation) and re-classification techniques.

**Specific minor comments:**

1. "Earth" should be "the Earth".

**Response:** We corrected it in the revision.

2. The phrase “under the content” appears in many places. I guess the authors meant to say “under the context”. But in many places there should be better expressions.

**Response:** We corrected it in the revision.

3. I see “for the domain” in several places. I am not sure what it means.

**Response:** “for the domain” that we used means “in the same region”. Maybe it is inapposite, so that we have deleted these words in the revision.

4. “Temporal-spatial” should be “spatiotemporal”.

**Response:** We corrected it in the revision.

5. The description of the NPP algorithm is hard to follow. If the authors decide to keep it, they should explain each symbol right below the equation where the symbol first appears.

**Response:** According to the major comment 5, we described the NPP products in the “2.1 Data”, meanwhile deleted the algorithm details from “2.2 Methods”.

6. Equation 8 is basic statistics; no need to include.

**Response:** We have deleted the Equation 8 according to the reviewer’s comment.

7. Line 20: should be “variable but positive trend”.

8. Line 21: should be “which is consistent”.

**Response:** We corrected them in the revision.

9. Line 22: “Trend” cannot be lower than “demand”; “deficit” cannot be “between”; what is “available water demand and supply for evapotranspiration”? This entire sentence needs to be rewritten.

**Response:** We have rewritten this entire sentence: “But precipitation increases cannot offset evaporative demand, indicating a potential moisture deficit for water supplies constrained by evapotranspiration. This leads to soil water loss and reduced”

10. Line 76: should be “came from”.

11. Line 97: should be “allows the use”.

12. Line 118: should be “the required MODIS data inputs for the ET algorithms”.



13. Line 129: should be “t-Test”.

14. Line 136: should be “While NPP in most part of NH increased, it decreased in most part of SH”.

**Response:** Thanks for the reviewer’s comments. We corrected the specific minor comments of 10-14 in the revision, respectively.

15. Line 156: should be “NPP and ET in SH have much higher variability in SH, where their association is less stronger than that in NH”.

**Response:** We have rewritten this entire sentence as follows: “NPP and ET in SH have much higher variability in SH, where their association is less than that in NH”.

16. Line 159: “stronger variability” of what?

**Response:** These regions have high values of average annual precipitation and stronger variability of precipitation than elsewhere.

17. Line 161: should be “In places where the inter-annual: : :”

18. Line 164: should be “controlling factor for NPP variation”.

19. Line 218: should be “proportional relationship”.

20. Line 221: should be “over the past 15-year period”.

**Response:** Thanks for the reviewer’s comments. We corrected the specific minor comments of 17-20 in the revision, respectively.

21. Line 221: what is “P”? Also see comments 7 and 9 above.

**Response:** We have rewritten this entire sentence as follows: “Global PET showed an increasing trend of 1.72 mm/yr<sup>2</sup> over the past 15-year period, while global P increased at a rate of 0.84 mm/yr<sup>2</sup>.”

22. Line 226: should be “affecting soil moisture”.

23. Line 227: should be “temperature and solar radiation may cause soil moisture loss through evapotranspiration”.

24. Line 231: Should be “Soil moisture is a common ecohydrologically confining factor”.

**Response:** Thanks for the reviewer’s comments. We corrected the specific minor comments of 22-24 in the revision, respectively.